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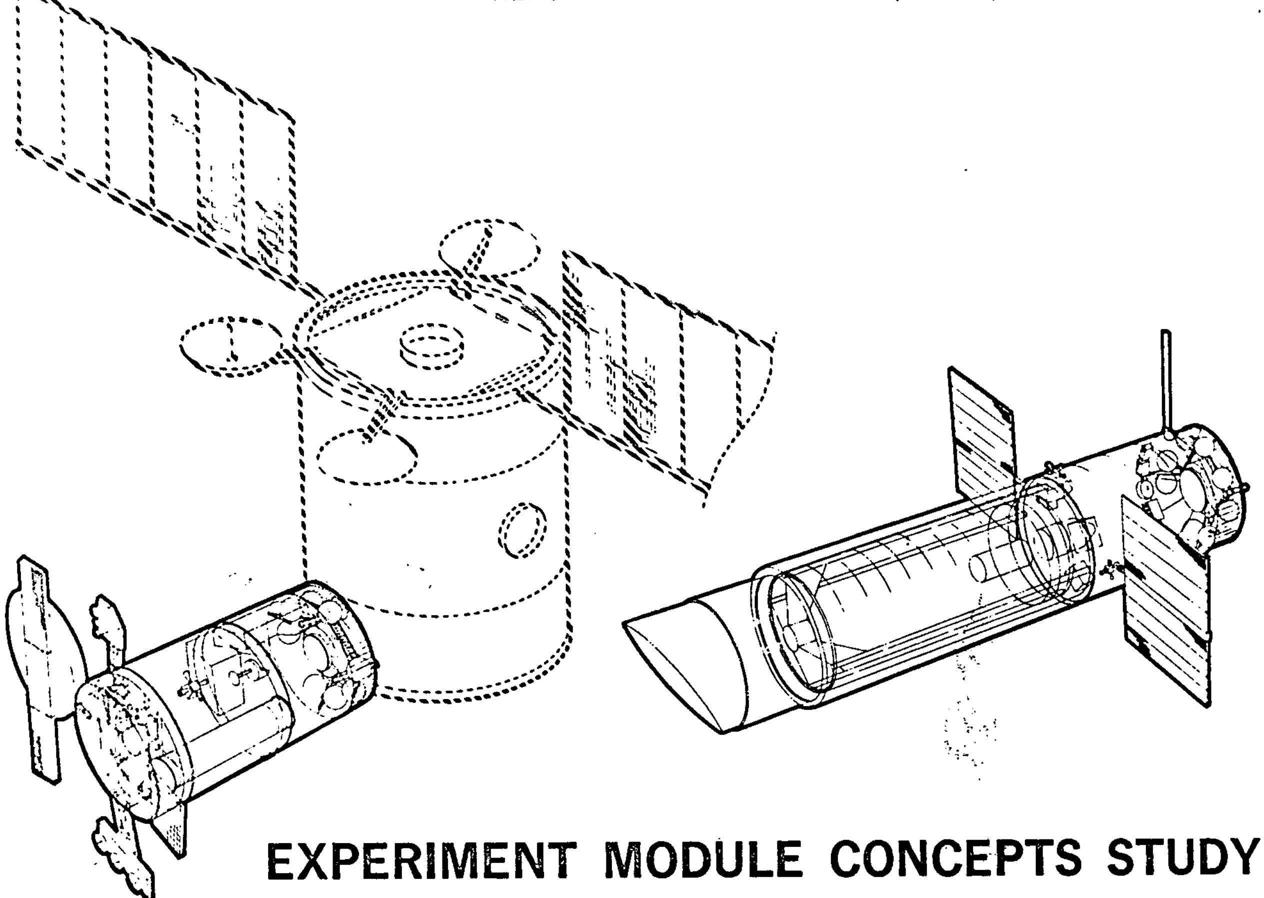

EXPERIMENT MODULE CONCEPTS STUDY

FINAL REPORT

VOLUME V BOOK 1 ✦ APPENDIX A SHUTTLE-ONLY TASK

October 1970

Prepared for
GEORGE C. MARSHALL SPACE FLIGHT CENTER
Huntsville, Alabama
Contract NAS8-25051

Advanced Space Systems, Research and Engineering
CONVAIR AEROSPACE DIVISION OF GENERAL DYNAMICS
San Diego, California

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VOLUME V
BOOK 1 ✦ APPENDIX A SHUTTLE-ONLY TASK

October 1970

Approved by: D. J. Powell

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FOREWORD

This final report is submitted in accordance with the requirements of Appendix 3 — Reports and Visual Aids Requirements, Statement of Work, Experiment Module Concepts Study, Contract NAS8-25051, as amended by Amendment No. 2 dated 9 March 1970.

It comprises the following documents:

Volume I — Management Summary
Volume II — Experiments & Mission Operations
Volume III — Module & Subsystem Design
Volume IV — Resource Requirements
Volume V — Book 1 Appendix A, Shuttle-Only Task
Book 2 Appendix B, Commonality; Appendix C, Maintainability

The study was conducted under the program and technical direction of Max E. Nein and Jean R. Olivier, PD-MP-A, of the George C. Marshall Space Flight Center, National Aeronautics and Space Administration. Dr. Rodney W. Johnson, OMSF (Code MF), as study sponsor furnished valuable guidance and assistance.

Other NASA centers and offices made significant contributions of advice, consultation, and documentation to the performance of the tasks, the results of which are reported here. Personnel from OMSF, OSSA, OART, MSFC, MSC, GSFC, LeRC, and Ames RC took part in periodic reviews during the study.

Convair Aerospace Division of General Dynamics was assisted by TRW Systems Group, Redondo Beach, California, in the performance of this contract. Personnel of both companies who contributed to this report are listed in Vol. I, Management Summary.

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OBJECTIVES AND GROUND RULES

OBJECTIVES

The primary objectives of this study are:

- To define the minimum number of standardized module concepts that will satisfy the NASA Candidate Experiment Program for Manned Space Stations at least cost.
- To define the module interfaces with other elements of the manned space program such as the space station, space shuttle, ground stations, and the experiments themselves.
- To define the total experiment module program resource and test requirements including SRT-ART.
- To determine the effect on experiment program implementation of shuttle-only operations.

GROUND RULES

The ground rules listed here evolved during the course of the study from the set provided at initiation of effort. They illustrate the reference framework within which results were developed.

General

Primary consideration will be given to the development of the minimum number of basic module concepts that through reasonable modification will be capable of accommodating all of the candidate experiment groups at least cost.

Experiments

1. NHB 7150.XX, "Candidate Experiment Program for Manned Space Stations" (Blue Book) will be used as an illustrative program of experiments to be integrated into the space station core module or into separately launched experiment/laboratory modules to assure that the system has the inherent capabilities to support those specific experiments and other experiments not yet identified.

2. Where not otherwise stated, the Blue Book period of experiment implementation will be two years.

3. All experiment equipment shall be assumed to have self-contained calibration capability.

Mission and Operations

1. The modules shall be capable of operating in conjunction with a space station in an orbit of 55 degrees inclination and 200-300 n.mi. altitude. The modules will not necessarily operate in this altitude range and inclination.

2. For a limited number of experiment groups the preferred alternate missionof sun synchronous (polar) orbit at an altitude of 200 n.mi. may be specified.

3. Experiment/laboratory modules may be operated in free-flying, docked, or permanently attached modes and may or may not be manned during their operation. However, all experiment modules operating in detached mode will be unmanned.

4. NASA will specify the operating mode and servicing mode for each experiment group. In some cases, concepts for particular experiment groups may be required for more than one operating and/or servicing mode.

5. Modules that operate in a free-flying mode and do not require the frequent attention of man for operation should have the capability of command and control by a station or logistics spacecraft.

6. Modules docked to the space station for servicing or operation should be assumed to be docked to a zero gravity station or a non-rotating hub of an artificial gravity station.

7. Unless a space tug is available, all modules designed for detached operation shall have the inherent capability of returning to and docking with the space station.

8. Rendezvous operations bring the module within 3000 feet of the space station with a maximum relative velocity of 5 ft/sec. Docking operations continue from there to contact. Automatic docking will be the preferred mode.

9. Attached modules shall have the capability of changing docked position on the space station once during a two-year period.

10. All detached modules shall operate depressurized.

Configurations

1. Where practical from a payload standpoint, the modules should be compatible with manned logistics systems consisting of Saturn IB-Modified CSM, Titan III - Big Gemini, S-IC/S-IVB-Modified CSM, and S-IC/S-IVB Big Gemini. Consideration should also be given to launching the modules in an unmanned mode on the above launch vehicles. The possibility of transporting the modules in an advanced logistics system should also be examined.

2. To the extent practical, experiment/laboratory modules will be designed to be compatible for launch on both expendable and reusable launch vehicles.

3. Modules and equipment will be designed for the axial and lateral accelerations associated with the launch vehicle specified.

4. Experiment equipment and module subsystems will be completely assembled/ installed on the ground and checked out prior to launch. Assembly in space will be avoided. However, to permit flexibility in updating equipment (and meeting maintenance requirements) designs should provide the capability for equipment replacement both on the ground and in orbit.

5. When docked to the space station, the modules will derive, for the most part, the electrical power, communications support, environmental control and life support, data processing facilities, and crew sytems needs (food preparation, hygiene, sleeping quarters) from the main space station. Careful attention should be given to the definition of the support required from the station and/or manned logistics spacecraft for each module and the module-station, module-logistics spacecraft, and module-experiment interfaces.

6. The experiment/laboratory modules will be designed for efficient utilization of the support services that the space station and the logistics systems can provide. The experiment/laboratory modules will supply services or supplement services that are inadequate (e.g., the space station cannot accept rejected heat).

7. All fluid interfaces with the space station may be assumed to be umbilical at the docking port.

8. A means will be provided to jettison modules from the space station as an emergency measure in event of a major hazard (fire, overpressure, etc.).

9. Modules shall be designed for a nominal two-year mission, with refurbishment in space at end of two years to extend life up to 10 years.

10. Servicing and maintenance of the modules and their experiments will be accomplished without EVA and in a shirtsleeve environment to the maximum practical extent. Possible exception to this would be the inspection and maintenance of externally mounted subsystems such as solar panels and RCS motors.

11. Means will be provided to accomplish inspection, servicing, repair and/or replacement of all equipment items not accessible from the module interior.

12. Modules will be designed for crew servicing, maintenance, and updating in a docked or hangared mode or by on-site repair from a docked tug.

13. Appropriate safety features (such as high voltage protection, adequate ingress/egress provisions, non-toxic and non-flammable materials, protrusion protection, etc.) will be incorporated into the design and maintenance aspects of each module concept. A crew safety analysis will be conducted to identify potential safety problems associated with the operation, servicing and maintenance of each module concept.

14. For the baseline module system no electronic data storage capability will be provided aboard modules. Centralized facilities on the space station/ground will be used. Over-the-horizon capability for detached modules will be studied as a modular add-on subsystem and costs.

15. Optical surfaces will be protected during the firing of RCS thrusters.

16. Leakage from pressurized modules will be assumed as follows:

0.08 lb per day per linear foot of breakable seal

0.04 lb per day per linear foot of static seal

0.0001 lb per day per square foot of pressurized surface area.

Shuttle-Only Mode

Ground rules peculiar to this task are given in Volume V, Appendix A.

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SECTION 1

INTRODUCTION AND SUMMARY

1.1 OBJECTIVES

The objective of the shuttle-only study task is to determine in a preliminary manner the effect on the NASA Candidate Experiment Program implementation of experiment modules' operations in the absence of an orbiting space station and with the availability of the space shuttle orbiter vehicle. Note that the results given apply in the context of the assumed ground rules only, as quoted in the following paragraphs.

1.2 TASKS

The following tasks were undertaken:

- Assessment of the feasibility and recommended operating modes for each FPE described in the Blue Book.
- Redefinition, if required, of the baseline common experiment modules and their experiment assignments for shuttle-only operation.
- Development of concepts for any support modules or kit additions required as substitutes for space-station-supplied support.
- Development of module/shuttle interface concepts.
- Development of a four-year, shuttle-only operating plan (1977-81) and preliminary program cost data.

1.3 GROUND RULES

- Man never leaves the shuttle/module complex or the crew module which must remain attached to the space shuttle at all times. Experiment modules may be left in orbit, either operationally or dormantly.
- Shuttle attitude hold capability is $\pm 1/2°$. Stability rates are $0.3°$/sec to $2.5°$/sec.
- Maximum time on-orbit is 5 days. However, the utility of a 30-day stay time will be examined.
- Maximum time to on-orbit is 48 hours (24 hr pad + 24 hr phasing). assuming that loading, topping, and chilldown on pad using umbilicals will be a requirement.
- Experiment modules will be self-sustaining while contained in the shuttle/payload compartment.

- Shuttle crew (2) are pilots only. They can perform routine service and crew module subsystems maintenance but only emergency experiment module servicing and maintenance. Critical module systems are to be monitored by the shuttle crew.
- Shuttle life support expendables are payload deductible to extend stay time of shuttle beyond 5 days. Shuttle will not provide extra EC/LS tankage. Two experimeters may utilize the shuttle EC/LS for up to 48 hours maximum per mission. Shuttle crew compartment is assumed habitable by a 2-man crew for 30 days.
- ~~Amount of RCS propellants required is to be identified during the study period.~~ If mission requirements exceed assumed 2000 lb capacity, penalty is payload deductible. Boiloff can be bottled up and vented at intervals.
- Experiment crew rides with the shuttle crew for launch and return.
- Experiment module is the active vehicle for docking to the shuttle. However, the shuttle will have the capability of active docking to the module. Shuttle will provide the active electronics for dockings.
- Allowable payload CG offset is 1.2 million ft-lb from the center of the cargo bay (i.e., no CG restriction on payloads under 40,000 lb).
- The McDonnell-Douglas ALS orbiter configuration from Space Station Phase B study will be used as baseline.
- Shuttle will provide payload deployment mechanism and standardized payload mounting.
- Maximum payload envelope is 15 ft - 0 in. dia. x 60 ft - 0 in. long.
- Limit load is 3g in any direction.
- RCS is bipropellant - GO_2/GH_2 - spark ignition - 1500 lb thrusters.
- Modules are loaded and checked out prior to shuttle movement to pad.

  Loaded horizontal or vertical

  5 days maximum time to pad

  Umbilicals are provided into cargo bay from ground/booster liftoffs

  Doors closed at T - 2 hours or as required by launch operation

  Perishables supplied through T - 0 from ground support

  Emergency access to the experiment module will be provided on the launch pad
- No cargo bay environmental control is available during flight. Prior to liftoff cargo bay is cooled as required from ground sources. No cargo bay acoustical level control is provided. Assume 24 hr liftoff to dock on-station. All module thermal control is self-contained during this period.

- Payload weight 25,000 lb to 270 n.mi. x 55° inclination orbit.
- Use ground track for guidance and navigation and experiment programming.
- Use current MSFN for data.
- Use current cost of shuttle launch ($4.0M).
- Crew module is not to be considered jettisonable as a "lifeboat." Deployment mechanisms retraction capability is a critical function for shuttle re-entry.
- Thermal condition of shuttle not known for module shadow.
- The shuttle will not provide the capability for control and command of free-flying experiment module.
- Experiment modules containing hazardous material will have self-contained protective devices or provisions against all hazards.
- All existing Blue Book FPEs will be considered for the shuttle-only studies.
- Hangar servicing will not be considered.
- Shuttle payload bay is not pressurizable in orbit.
- Expendable launch vehicles will not be considered in conjunction with the shuttle-only operating modes.

1.4 SUMMARY OF RESULTS

The fundamental hardware elements for shuttle-only operation of the NASA candidate experiment program are:

a. Integrated common experiment modules CM-1 (free flying), CM-3, and CM-4 (attached), together with the propulsion slice

b. Support modules capable of supplying on-orbit crew life support, power, data management, and other services normally provided by a space station — this for periods of up to five or up to 30 days

c. Dormancy kits (power, data management, etc.) to enable normally attached experiment modules to remain in orbit while the shuttle orbiter returns to earth.

d. The shuttle orbiter itself.

The support modules are basically derivatives of the CM-3 common module.

Several support/experiment module combinations exceed the shuttle payload bay length of 60 ft. All combinations exceed the 25,000 lb to 270 n.mi./55 deg orbiter payload capability and are accommodated by launch to lower altitude/inclination orbits or by launch separately with subsequent orbital rendezvous.

Experiment requirements can in general be satisfactorily met. Where the orbiter stability is inadequate, experiment module subsystem capability is used. The preferred ground station system for data handling is an updated MSFN with 10 Mb/s digital and 16 MHz RF video/analog capability.

The support module itself weighs about 11,800 lb for a 2-man, 5-day stay version, 16,300 lb for a 2-man, 30-day stay version, and 20,500 lb for a 4-man, 30-day stay version.

Utilization of the 5-day stay version was found early to force an unreasonable number of shuttle flights in order to implement the experiment program and to deny certain experiments altogether. The 30-day stay capability, however, increased experiment realization while reducing the number of supporting shuttle flights and hence the overall program cost.

Preliminary program cost estimates are:

a.	Approximate full experiment program with 30-day on-orbit capability	$4.2B
b.	Approximate full experiment program with 5-day on-orbit capability	$6.0B
c.	Restricted experiment program with 5-day on-orbit capability	$2.1B

These costs are for a four-year implementation period and cannot be directly compared with the costs derived in the mainline study for a space-station-supported experiment module program since no prorating of space station costs for module support was made.

If the shuttle orbiter is to support experiment module operations of the type discussed in this report, then the impact of these requirements should be reflected in orbiter design. Two important requirements uncovered are for a minimum 30 days on-orbit stay time, and for RCS sizing in the 150-lb thruster range to supplement the existing 1500-lb thrusters and minimize stabilization propellant requirements.

A viable experiment program can be conducted in the shuttle-only mode under the conditions quoted. The experiment module concepts already developed are compatible with this mode of operation. The support modules required exhibit considerable commonality with the experiment module concepts. Implementation in the 30-day stay mode requires 7 free-flying modules, 10 attached modules, one propulsion slice, 10 support modules and 213 supporting shuttle flights over a four-year period.

SECTION 2

EXPERIMENT IMPLEMENTATION

This section establishes functional, performance, and operational requirements and identifies recommended shuttle-only operating modes for accommodating the complete list of FPEs (5.1 through 5.27) for a four-year period. During this four-year period the experiment modules are delivered to orbit, supported, and serviced from the space shuttle. Modules operate out of and are supported from the space station following the initial shuttle-only operational period.

Requirements for space station substitutes and methods of implementing these substitutes are defined. Experiments and experiment module subsystems are incremented from the baseline (space station based) designs to accommodate the FPEs in the shuttle-only mode. Subsystem designs are also incremented to reflect the revised maintainability approach for the shuttle-only program. Mission timelines are prepared and form the basis for a four-year launch schedule and operations plan.

The majority of the NASA Candidate Experiment Program can be accomplished using shuttle-only support to the experiment program. The experiments affected by this mode of operation are:

- FPE 5.3A Solar Astronomy - real-time observer control if limited.
- FPE 5.8 Cosmic Ray Lab - experiments using nuclear emulsions are time limited.
- FPE 5.9/X Biology - requires automation for 40-hour periods.
- FPE 5.13/X Aeromedicine - man's stay time in orbit is 30 day maximum.

Other experiments affected, to a lesser degree, FPE 5.17 Contamination and FPE 5.24 Engineering and Operations are discussed in Section 2.4.4 of this volume.

A support module interfaces between the orbiter and the experiment modules providing a space station substitute. The baseline support module accommodates an experiment crew of two for five days on-orbit. However, the use of a support module with 30-day stay-time capability and a crew of two or four was also investigated where required by the experiment or when the incremented support module held promise of reducing program costs. Portions of the Aeromedicine group of experiments (FPE 5.13/14/15) require at least a crew of four, and one part of FPE 5.24d (MSF Engineering and Operations — Advanced Orbital EVA) requires a minimum crew of three. The four-year operations program requires 555 shuttle launches with a 5-day stay time support module and 213 launches with a 30-day stay time support module.

2.1 OPERATIONS CONCEPTS

The shuttle-only study is an investigation of the feasibility of supporting space experiments packaged in experiment modules with the space shuttle. This program is a precursor to a continuing experiment program where experiment modules are supported by the space station following a four-year shuttle-only program.

During the precursor program all on-orbit experiment support is supplied by the space shuttle. Major ground rules that strongly impact shuttle-only operations concepts are:

a. Manned modules will remain attached to the shuttle at all times.

b. Experiment modules may be left in orbit either active or dormant.

c. Maximum shuttle time on-orbit is 5 days — utility of 30 days to be examined.

d. Shuttle crew not available for experiment work.

e. Shuttle crew life support expendables are payload deductible beyond 5 days.

f. Experimenters ride in shuttle crew compartment for launch and return.

g. Crew support modules not to be considered jettisonable as lifeboats.

h. All Blue Book FPEs will be considered.

i. Shuttle payload capability 25,000 lb to 270 n.mi./55 deg.

2.1.1 BASIC CONCEPTS. With these constraints and ground rules as a starting point, a number of potential operation concepts were investigated. Four concepts were selected for further study as shown in Figure 2-1. Each concept contains means for supporting the experiment crew of scientist-astronauts and for providing the necessary substitutions for support normally provided by the space station. This support is contained within a new module, called a support module, for operations Concepts A, B, and C. In Concept D the support is furnished by a kit incorporated within the experiment module.

Concept A applies primarily to free-flying astronomy modules. Experiment modules are delivered to orbit and the experiments are activated by the crew housed in the support module. The experiment module can be launched separately and then docked to the support module which in turn is attached to the shuttle orbiter during this period. Following experiment activation, the experiment module is undocked from the support module, transferred to its station keeping orbit, and data recording is initiated. Experiments are automated and remain on-orbit for years. Periodic on-orbit servicing is provided by a crew boosted to orbit by the shuttle together with a support module. A data management kit is added to these modules to direct the experiments during free-flying periods and to record and subsequently transmit the recorded data to ground stations.

Concept B applies primarily to experiments that can be effectively accomplished through repeated, short-duration stay times in orbit. The experiment module remain attached to the support module and both are delivered to orbit and returned to earth by the shuttle for each experimentation period. Man is in attendance or available during all experiments.

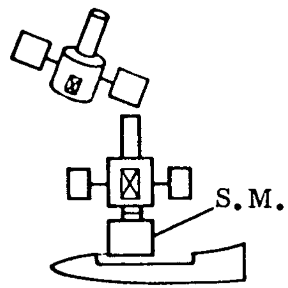
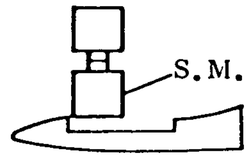
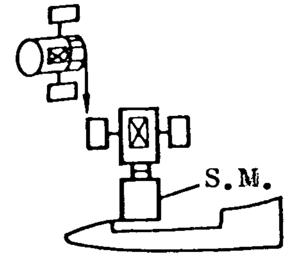
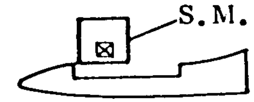
	A	B	C	D
OPERATE CONCEPTS SERVICE		 EARTH	 ON-ORBIT OR EARTH	 EARTH
PREFERRED ORBIT	270 N.MI. x 55°	VARIES	270 N.MI. x 55°	ANY
EXPERIMENT • DURATION	YEARS	5 TO 30 DAYS	TO 30 DAYS + AUTOMATED	5 DAYS
• MANNING	UNMANNED	MANNED	MANNED + AUTOMATED	MANNED
• EQPT CHANGE	1-2 PER YR.	FREQUENT	INFREQUENT	FREQUENT
• SERVICING	2-3 MO.	FREQUENT	INFREQUENT	FREQUENT
MODULE TYPE	FREE-FLYING	ATTACHED	ATTACHED & FREE-FLYING	ATTACHED

Figure 2-1. Operations Concepts Shuttle-Only Study

Concept C applies primarily to experiment laboratories where equipment is changed relatively infrequently, or where experiments can be carried aboard in suitcase form. Experiment modules are left on-orbit in a dormant status when not in use. They are delivered to orbit by the shuttle and are used for manned experiments only when docked to a support module. Unmanned, automated experiments are continued during the dormant phase. The scientist-astronauts, new experiments, and supplies are brought to orbit by the shuttle for each experimentation period. Experiment modules can also be used for short-duration free-flight tests in the near vicinity of the shuttle orbiter/support module. A dormancy kit is added to experiment modules to provide data management, power, cooling, and stability and control during dormant periods.

Concept D applies primarily to experiment modules, which have adequate volume or can be off-loaded to permit retrofit of a crew habitability kit. This kit houses a two-man crew and provides facility support for short stays on-orbit. The shuttle delivers this module to orbit for each experiment period and returns with the shuttle orbiter.

2.1.2 SPACE SHUTTLE CONFIGURATION. The McDonnell-Douglas orbiter configuration is used as a baseline. Sketches of this configuration showing detached and attached experiment modules and a support module are shown in Figures 2-2 and 2-3. The support module is carried within the orbiter cargo bay during boost as shown in Figure 2-2, and the scientist-astronauts ride in the orbiter crew compartment. Access from the orbiter crew quarters to the support module is provided through a tunnel. An experiment module docked to a support module can be carried within the cargo bay if the weight and length of the combination are within acceptable limits. This arrangement is shown in Figure 2-3.

When an experiment is to be activated, the support module (and the experiment module if carried to orbit on the same launch) is rotated out of the cargo bay through 90 deg as shown in Figure 2-3. This is the normal position for servicing modules and for conducting experiments when modules are attached. If only the support module is boosted to orbit, the support module is rotated to the 90 deg position, and the free-flying module is then docked to the support module.

Shuttle constraints that significantly impact shuttle-only operations are:

a. Attitude hold capability is ± 0.5 deg with a minimum stability rate of 0.3 deg/sec.

b. Maximum time to on-orbit is 48 hours (24 hours on the pad plus 24 hours maximum transit and phasing).

c. Docking is accomplished only between a support module and a detached experiment module.

d. The maximum payload envelope is 15 ft - 0 in. diameter by 60 ft - 0 in. in length.

e. Modules will be placed at other than 270 n.mi. x 55 deg only when shuttle payload capability is otherwise exceeded, or experiment requirements may be better fulfilled.

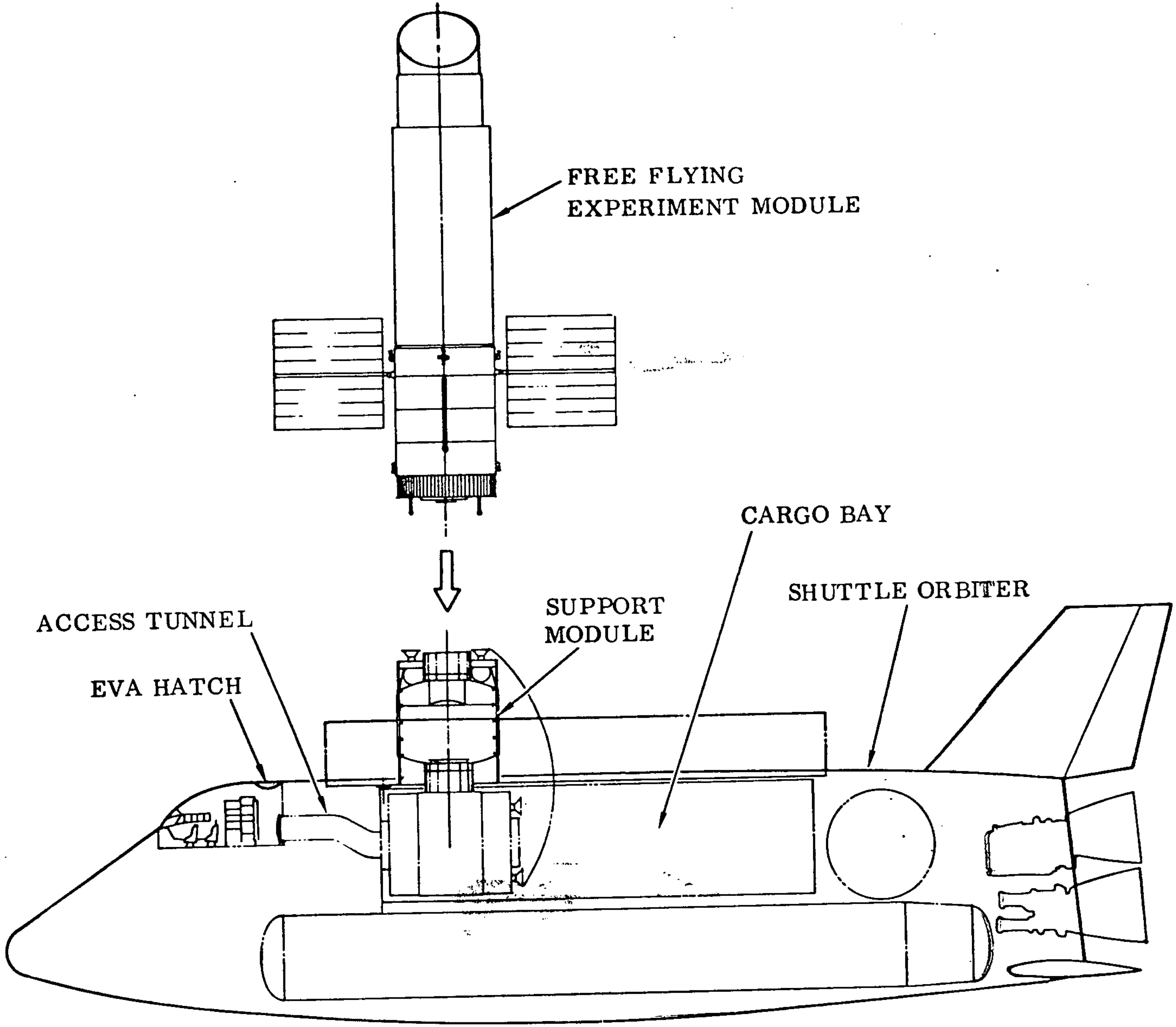


Figure 2-2. Free-Flying and Support Modules

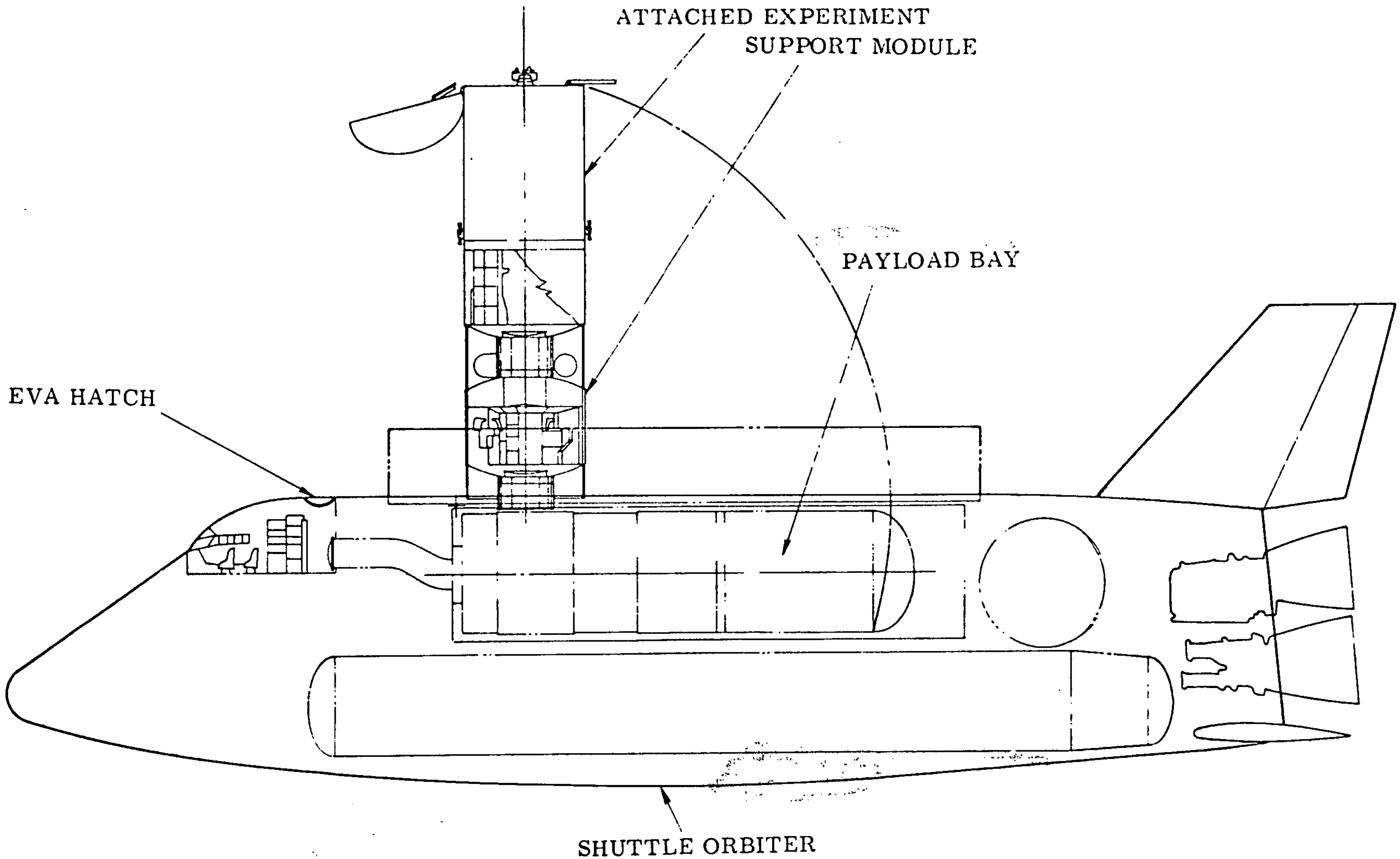


Figure 2-3. Attached Experiment and Support Modules

2.1.3 PERFORMANCE CONSIDERATIONS. The basic shuttle payload capability was stated in the ground rules as 25,000 lb to a 270-n.mi. orbit at 55 deg. Figure 2-4 is a cross plot of shuttle circular orbit payload capability at orbit inclination angles of 55 and 28.5 deg. There are several methods of using this capability to deliver the experiments to orbit:

a. Lightweight experiment modules, under 25,000 lb, can be delivered to the generally desired 270 n.mi. x 55 deg orbit directly by the shuttle. However, a support module is required, at least for experiment initiation, and the combined experiment and support module weight exceeds this capability in all cases. Therefore, experiment and support modules cannot be delivered together to the 270 n.mi. x 55 deg orbit.

b. Where the inclination angle is not critical and/or orbital altitude can be reduced, both the experiment and the support module can be delivered to orbit at the same time. For example, shuttle payload capability is 38,500 lb to a 200 n.mi., 28.5 deg inclination orbit.

c. Heavy experiment modules exceeding 25,000 lb can be delivered to the 270 n.mi. x 55 deg orbit by using the experiment module RCS propulsion system to increase orbital altitude. The shuttle delivers the module to a lower, interim altitude orbit (e.g., from Figure 2-4, a 30,500-lb module can be delivered to a

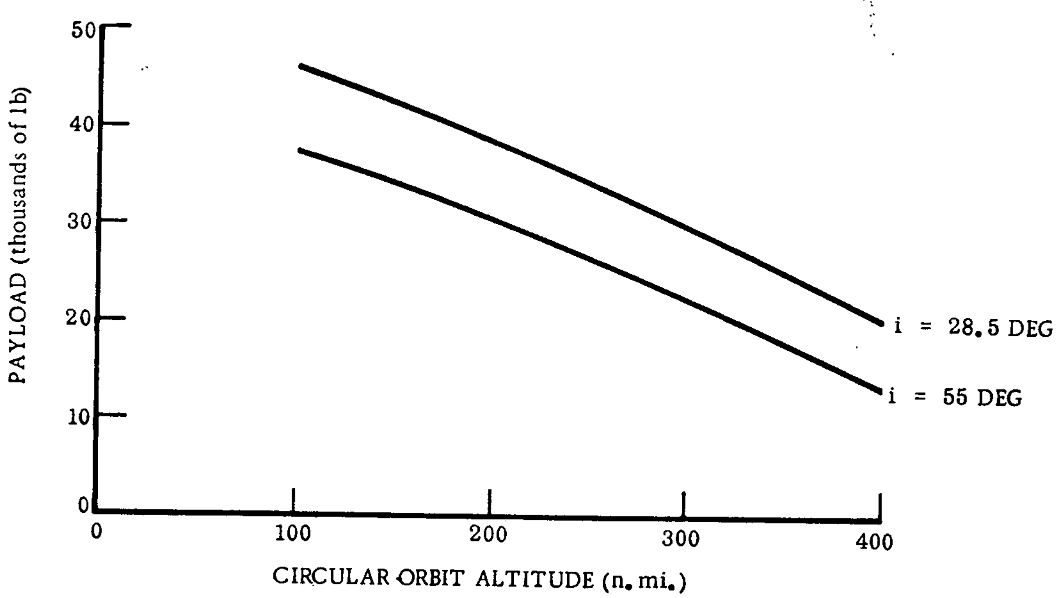


Figure 2-4. Shuttle Payload Capability (25,000-lb Space Shuttle)

200 n.mi. orbit at a 55 deg inclination). The experiment module then undocks from the orbiter and using its RCS propulsion executes a Hohmann transfer to the 270 n.mi. orbit. A second shuttle launch is then required to boost a support module and the experiment crew to the experiment module for initial activation. Figure 2-5 shows the maximum experiment module weight deliverable to a family of final orbit altitudes (200, 230, and 270 n.m i.) following boost by the shuttle to an interim orbit. Modules weighing up to 44,000 lb can propel themselves from a 200 n.mi. orbit to a 270 n.mi. orbit.

d. The lightest weight modules can be delivered in another manner which saves one shuttle launch. Both experiment and support modules are launched to a low earth orbit — from Figure 2-4, a combined weight of 35,000 lb can be boosted to a 140 n.mi. x 55 deg orbit. The experiment crew activates the experiment in this orbit; the experiment module then undocks and executes the transfer maneuver to 270 n.mi. where the data recording period starts. Figure 2-5 shows that an experiment module weighing up to 23,500 lb can transfer itself from a 140 to a 270 n.mi. orbit.

2.1.4 CREW WORK-REST CONSTRAINTS. The nominal crew work period does not exceed 10 hours per man per day for a 6-day week in accordance with the space station ground rules. Within the 10-hour work period it is assumed that the time available for

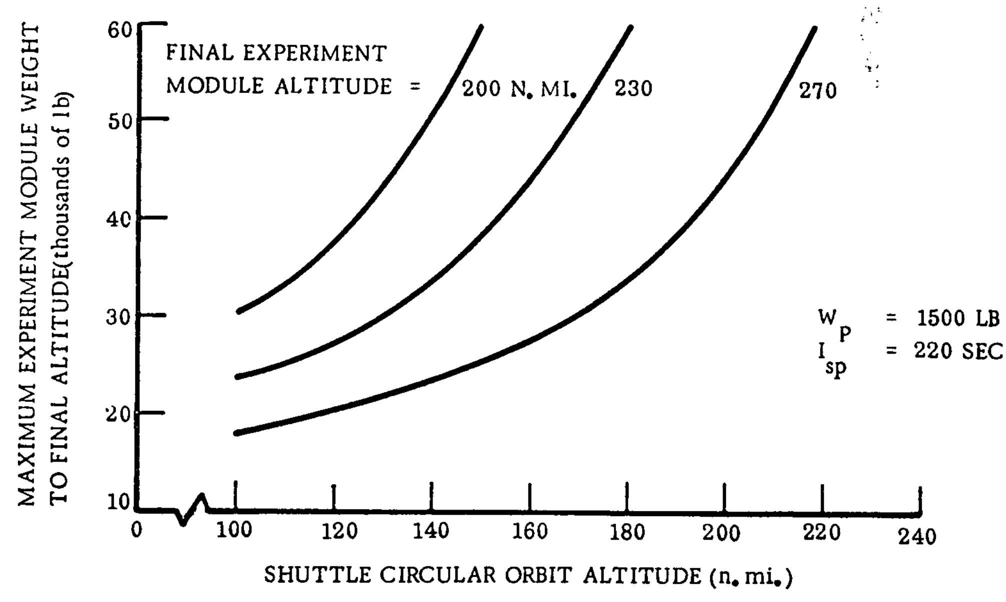


Figure 2-5. Experiment Module Transfer Orbit Capability

experiment observation and measurement program will vary between 8 (Case 1) and 10 (Case 2) hours as shown in Table 2-1. The number of shuttle flights required to accomplish several of the experiment FPEs is sensitive to the number of experiment man-hours. For a 2-man crew, a nominal 16 man-hours/day are available 6 days a week. Most of the experiment related tasks require two men at least part of the time and usually with different skills. For this reason a single-shift operation is utilized. Shuttle flights could be reduced significantly if four men were available for certain experiments; this option is discussed further in Section 2.4.

Table 2-1. Experiment Crew Time

Activity	Hours/Day/Man	
	Case 1	Case 2
Experiment observation and measurement	8	10
Other work (e.g., module maintenance)	2	0
Total work time available	10	10
Other activities	14	14
Total	24	24

2.1.5 <u>SHUTTLE TURN-AROUND TIME CONSTRAINT.</u> The nominal shuttle system ground turn-around time is 14 calendar days. This is based on 10 working days with two 8-hour shifts/day. Functions accomplished during the turn-around period include post-landing servicing and safing maintenance, booster/orbiter/payload mating, transportation, erection, and launch operations. Present estimates place the time available for payload operations at six to eight working days.

2.2 EXPERIMENT REQUIREMENTS

The governing criteria for development of experiment and support module concepts for the shuttle-only study are those requirements placed by the experiments on module design and operations. These requirements are grouped in three general categories:

a. Facility type support: electrical power, data transmission, experiment equipment weight and mounting structure, etc.

b. Environmental control: radiation, contamination and acceleration.

c. Orientation: direction, accuracy and stability.

Determination of module design and operations requirements fall into four areas of analysis: experiment requirements on module subsystems, support module requirements, program launch requirements, and experiment duty cycle requirements and pointing accuracy.

2.2.1 EXPERIMENT REQUIREMENTS ON MODULE SUBSYSTEMS. Experiment requirements are summarized in Table 2-2. Requirements were originally derived from Blue Book definitions of experiment equipment and program requirements and summarized in Convair Report No. GDC-XM-TN-160 (Volume II). These requirements have recently been updated to reflect continuing improvement in experiment definitions.

Stability and pointing requirements reflect those values which are necessary for proper operation of the experiment. These requirements may be met by experiment peculiar, module, or shuttle orbiter stability control systems acting singularly or in combination. Experiment module and orbiter stability and pointing requirements during periods when experiment modules are attached to support modules at the orbiter are discussed in Section 2.2.4.

2.2.2 SUPPORT MODULE REQUIREMENTS. Support modules act as space station substitutes during the shuttle-only program. The number of support modules is sensitive to launch interval, and the four-year program plan. A maximum of 10 support modules is required using a minimum shuttle turn around time of 2 weeks. Program requirements for support modules are shown in Figure 2-6. Support modules used for servicing free-flying modules must be capable of at least 12 round trips per year for a 3- to 4-year period. Commonality of support modules is emphasized to reduce costs and specialized ground and flight crew training and equipment. Necessary support module functions and performance capabilities due to experiment requirements for a two-man support module are shown in Table 2-3.

2.2.3 PROGRAM LAUNCH REQUIREMENTS. Requirements for shuttle launches can be subdivided into initial launches, recurring experiment operation launches, recurring service and experiment update launches, and recovery launches. The number of shuttle launches is also a function of on-orbit stay time and module weight and length. Launch requirements are summarized in Table 2-4. Payload weight and length effects on number of launches are considered and expressed in terms of additional initializing launches. Experiments with compatible requirements have in several cases been assigned to a single module.

Service launches are required for delivery of film, cryogenic, and other expendables, and experiment rearrangement or planned experiment maintenance. Astronomy modules share service launches at a nominal rate of 1/3 flight per module, repeated 6 times per year using a baseline 60-day interval. Additional launches are necessary for 30-day service intervals. FPE 5.8 (Cosmic Ray) as presently defined requires approximately one complete 5-day service period every 30 days.

The Brayton cycle isotope power system (FPE 5.24c) remains on orbit for a two-year test. After initial operation capability is achieved, service launches will be required at intervals of from 60 to 180 days. Propellant servicing for stability control will be required after about 180 days of free-flight.

Table 2-2. Experiment Requirements Summary

Parameter	X-ray 5.1	Stellar 5.2A	Solar 5.3A 1,2,3	UV Stellar 5.4	Hi Energy 5.5 -1,-2	Airlock Physics 5.6	Plasma Physics 5.7/ 5.12	Cosmic Ray 5.8	Biology 5.9 5.10	Earth Surveys 5.11	Aeromedicine 5.13/ 5/13C	Aeromedicine 5.14	Aeromedicine 5.15	Materials Science 5.16	Contamination 5.17
Orientation	Stellar	Stellar	Solar	Stellar	Stellar	—	—	Zenith	—	Earth	—	—	—	—	—
Pointing	(7)	(7)	(7)	(7)	(7)	(7)				(11)					
Accuracy	±2 $\widehat{\text{min}}$	±10 $\widehat{\text{sec}}$	±2.5 $\widehat{\text{sec}}$	±5.0 $\widehat{\text{sec}}$	±15 $\widehat{\text{sec}}$	±1 deg	±0.5 deg	±30 deg	—	±0.5 deg	—	—	—	—	±0.1 deg
Stability	1 $\widehat{\text{sec}}$/sec	0.005 $\widehat{\text{sec}}$/sec	0.01 $\widehat{\text{sec}}$/sec	0.5 $\widehat{\text{sec}}$	3.0 $\widehat{\text{sec}}$/sec	0.012 deg/min	0.3 deg/sec	—	—	0.03 deg/sec	—	—	—	—	0.01 deg/sec
Acceleration (g) Constraints	—	—	—	—	—	—	—		10^{-3} 10^{-5}	—	2×10^{-3}	—	—	10^{-2} 10^{-5}	—
Weight (lb)															
Experiment	3300	8300	7345	1550	7800	600	6325	19,500	6355	4550	1950	1100	1070	5390	850
Special Support	—	—	—	—	—	—	—	—	800(10)		1000(1)	(3)	—	—	—
Data											(2)				
Digital Rate (BPS)	10×10^3	1×10^6	1×10^6	—	10×10^3	4×10^3	400×10^3	50×10^3	160×10^3	132.5×10^3	125×10^3	100×10^3	100×10^3	1×10^3	63×10^3
Analog Bandwidth	—	—	—	—	—	—	—	—	—	4 mHz	—	—	—	1 Hz	
TV Channels	1	1	3	1	1	-	1	1	2	1	1	1	1	1	2
Film Required	-	Yes	Yes	Yes	Emulsions	-	Film	Emulsions	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Electrical Power															
Average (kW)	0.25	0.69	0.32	0.12	0.44	0.05(8)	5.25 (15 min./ orbit)	2.85	1.32	5.0 (15 min./ orbit)	0.75	0.50(4)	0.70	2.0 (4 hrs)	0.4
Peak (kW)	0.30	0.93	0.51	0.125	0.60				1.67	5.8	1.25	1.0(4)		5.0	0.5
Cryogenic Supply Required	Yes	—	—	—	Yes	—	—	Yes	—	Yes			—	Yes	—
Contamination Sensitive	Yes	Yes	Yes	Yes	Yes	Yes	—	—	—	Yes	—	—	—	Yes (12)	Required
Radiation Sensitive (Below Personnel Level)	Yes	—	—	Yes	Yes		Magnetic	Yes	—	—	—	—	—	—	—
Crew	2 (6)	2 (6)	2 (6)	2 (6)	2 (6)	2	2	2 (6)	2	2	2-4	2 min. (5)	2	2	2 EVA

Parameter	Exposure 5.18	Fluid Physics 5.20 -1	Fluid Physics 5.20 -2	Fluid Physics 5.20 -3	Fluid Physics 5.20 -4	IR Stellar 5.21	Component Test 5.22	Primates (B10A) 5.23	MSF Engineering & Operations 5.24 bA	5.24 bB & bC	5.24 c	5.24 d&e	5.24 f&g	5.24 h	5.24 i	Micro-Biology 5.25	Invertebrates 5.26	Physics & Chemistry 5.27
Orientation	Earth	—	—	—	—	Stellar	Earth	—	—	—	—	—	—	—	—			—
Pointing							(7)			(7)								
Accuracy	—	—	—	—	—	±1.0 $\widehat{\text{sec}}$	±30 $\widehat{\text{sec}}$	—	—	0.01 $\widehat{\text{sec}}$	—	—	—	±0.5 deg	±0.1 deg			
Stability	—	—	—	—	—	0.1 $\widehat{\text{sec}}$	7.2 $\widehat{\text{sec}}$/sec	—	—	—	—	—	—	0.3 deg/sec	0.0005 deg/sec			
Acceleration (g) Constraints	—	10^{-4}	Sust. Accel @ 10^{-3}, 10^{-4}, 10^{-5}, 10^{-6}			—	10^{-2}	10^{-3}	—		—	—	—			10^{-4} 10^{-5}	10^{-2} 10^{-3}	10^{-3} 10^{6} (14)
Weight (lb)																		
Experiment	400	785	5000	3010	5250	2250	2000	4500	37,000	3800	4000	2545	3490	2285	530	160	400	7185
Special Support	—	—	—	—	—	—	—	—	—	—	(17)	—	—	—	(18)	(19)	(19)	
Data																		
Digital Rate (BPS)	8.4×10^3	1×10^3	5.78×10^3	6×10^3	6×10^3	1×10^6	38×10^3	200×10^3	5×10^3	15×10^3	3.5×10^3	100×10^3	5×10^3	4×10^3	2×10^3	$.5\times10^3$	$.5\times10^3$	1×10^3
Analog Bandwidth	100 Hz	—	—	—	—	—		—	—	—	—	—	—	—	—	—	—	—
TV Channels	-	1	6 (13)	1	2	1	1	1	—	2	—	1	1	—	—	1	1	1
Film Required	-	Yes	Yes	Yes	Yes	Yes	Yes	Yes	—	—	—	Yes	Yes	—	—	Yes	Yes	Yes
Electrical Power																		
Average (kW)	0.143	0.25	0.17	0.18	0.16	0.30	1.0 (4 hrs)	2.0	1.05 (15)	1.25 exp. 1.5 support	0.5	2.1	1.2	10.0	0.23	0.42	0.32	0.5 (orbit avg.)
Peak (kW)	0.26	0.25	1.4	7.6	1.2		2.15	2.0		(16)								3.0
Cryogenic Supply Required	—	—	—	Yes	Yes	Yes	Yes	—	—	—	—	—	—	—	—	—	—	—
Contamination Sensitive	—	—	—	—	—	Yes	Yes	—	—	Yes	—	—	—	—	Yes	—	Yes	Yes
Radiation Sensitive (Below Personnel Level)	—	—	—	—	—	—	—	—	—	—	Rad. Source	—	—	—	—	—	—	—
Crew	2 EVA	2	2	2	2	2 (6)	2	2	2	2	2	2-3	2	2	1	2	2	2

Notes:
(1) Manned centrifuge - not incl. housing
(2) Includes centrifuge + IMBLMS
(3) Shares IMBLMS equip. & centrifuge
(4) Not including manned centrifuge
(5) Uses all available crew
(6) Service crew
(7) Spacecraft provides different pointing/stab. level
(8) Plus support system power
(9) Includes bio-centrifuge
(10) Bio - centrifuge without housing
(11) Requires truth site pointing ±60 deg
(12) Requires vacuum and pressure
(13) Reduced bandwidth acceptable
(14) Plus sustained accel @ 10^{-3}, 10^{-4}, 10^{-5}, 10^{-6}g for 2 experiments
(15) Support module equip. exp. supplies other pwr.
(16) Equipment is located in separate modules
(17) Not incl. large housing and radiator
(18) Requires laser receiver at synchronous altitude
(19) Shares lab equipment and bio-centrifuge - ref. FPE 5.9/5.10

FOLDOUT FRAME 1

FOLDOUT FRAME 2

FOLDOUT FRAME 3

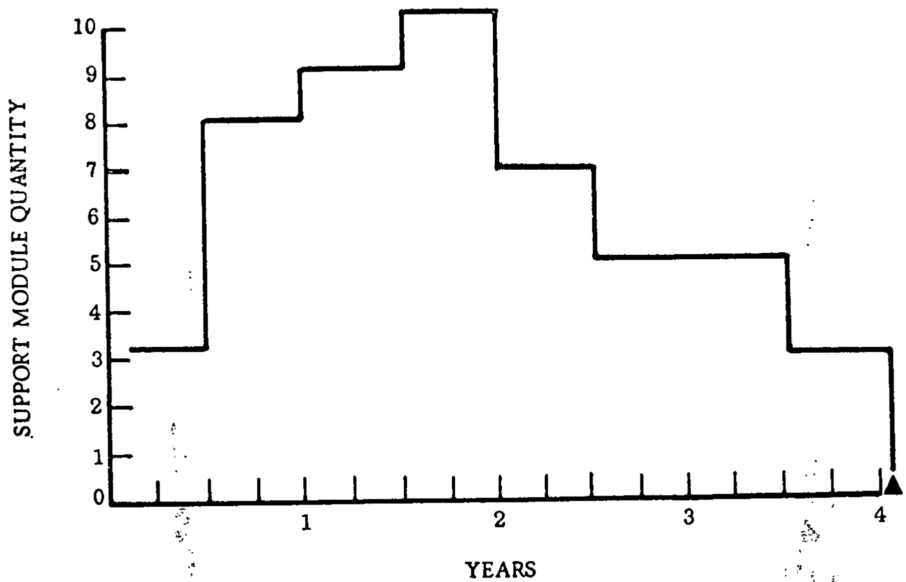


Figure 2-6. Support Module Quantity

One launch for yearly experiment updating is allocated to each astronomy and cosmic ray modules. Updating may be accomplished on-orbit or on the ground depending on the complexity of the planned update operations. Earth surveys sensors are updated once every two years. Other modules do not have special updating flights due to the planned frequency of normal experiment operations flights.

Table 2-3. Experiment Requirements on Support Modules

Module Function	Module Requirement
Crew EC/LS	Shirtsleeve environment for 2 scientist-astronauts for 5 to 30 days plus expendables for 2 shuttle crew men for up to 25 days. Two hours pressurization time for Astronomy experiment modules
Crew habitability	Two men for up to 30 days.

Table 2-3. Experiment Requirements on Support Modules, Contd

Module Function	Module Requirement
Data	Hardline link to attached module TV link.
	Two-way voice — shuttle and experiment module.
	Critical function monitor — hardline to shuttle.
Guidance/navigation	Active laser docking elements.
Physical	Neuter docking mechanism.
	Five-ft diameter (minimum) docking port.
Thermal	Experiment peculiar electrical heat load.
Stability/control	None.
Propulsion	Refill module tank — 2500 lb hydrazine.
	Refill propulsion slice tank — 4900 lb hydrazine.
	Fluid transfer control.
Electrical power	1500 watts (avg.) for 5 days.
Logistics	Maximum envelope for a 30-day period: 1500 - 2500 lb film & film storage; 200 lb LH_2, 225 lb LN_2, 800 lb LO_2 test fluids; 950 lb animal support; 1500 lb pressurization gas.

Module recovery flights are scheduled for the Brayton cycle isotope power system; the supporting experiment module is recovered at the same time.

The annual experiment operations launch rate and nominal on-orbit period are also shown in Table 2-4 for each FPE. Launches are based on a 30-day on-orbit capability. Additional launches are required for those FPEs that can be accomplished with a series of five-day experiment periods.

Shuttle launch requirements for both 5- and 30-day programs are summarized in Table 2-5. A support module and a shuttle orbiter with a 30-day (maximum) capability is assumed for the 30-day (maximum) number of launches. Program launch schedules become important when the annual rates shown in Table 2-4 are converted into total launches for each FPE. Operational program durations are discussed in Section 2.3.3. Table 2-5 shows that the number of launches for astronomy modules is the same for both the 5- and 30-day cases, reflecting the use of a 30-day capability module for a 5-day mission. Nearly constant manned attendance may be desirable for some FPEs and is necessary for the biology experiments. Shuttle launch requirements are considerable for a 30-day operating mode, and may be prohibitive for a 5-day capability.

Table 2-4. Launch Requirements — Shuttle-Only

FPE	Title	Initial Support Module Launch		Experiment Peculiar Launch		Initial Module Launch*		Annual Experiment Operations Launch*		Annual Service Launch		Annual Experiment Update Launch		Recovery	
		No.	Shuttle Stay Time (days)	No.	Shuttle Stay Time (days)	No.	Shuttle Stay Time (days)	Rate	Shuttle Stay Time (days)	Rate	Shuttle Stay Time (days)	Rate	Shuttle Stay Time (days)	No.	Shuttle Stay Time (days)
5.1	X-Ray	—		—		1	5	—		2/yr†	5	1/yr	5	—	
5.2A	Stellar	1	5	—		1	5	—		2/yr†	5	1/yr	5	—	
5.3A-1, -2, -3	Solar	1	5	—		1	5	—		8/yr†	5	1/yr	5	—	
5.4/5.21	UV/IR Stellar	—		—		1	5	—		2/yr†	5	1/yr	5	—	
5.5	High Energy	—		—		1	5	—		2/yr†	5	1/yr	5	—	
5.8	Cosmic Ray	1	5	—		1	5	—		12/yr	5	1/yr	5	—	
5.9/x	Space Biology	1	5	—		—		12/yr	30	—		—		—	
5.11	Earth Surveys	1	5	—		—		12/yr	5-25	—		1/2/yr	5	—	
5.6/5.7/5.12	Space/Plasma Physics	1	5	—		—		4/yr	15-30	—		—		—	
5.13/5.14/5.15	Aeromedicine	1	5	—		—		6/yr	30	—		—		—	
5.16	Materials Science	—		—		—		6/yr	30	—		—		—	
5.17/5.18	Contamination/Exposure	—		—		—		—		—		—		—	
5.20-1	Fluid Physics (Attached)	—		—		—		1/yr	30	—		—		—	
5.20, -2, -3, -4	Fluid Physics (Detached)	—		2	5	1	5	3/yr	30	—		—		—	
						1	5	6/yr	10						
						1	5	10/yr	5						
5.22	Component Test	1	5	—		—		3/yr	30	—		—		—	
5.24b	MSF Engineering & Operations	2	5	2	5	—		1/yr	20	—		—		—	
5.24c		—		1	5	—		4/yr	30	5/yr	5	—		2	5
5.24d		—		—		—		1/yr	20	—		—		—	
5.24e		—		—		—		0	10	—		—		—	
5.24f		—		—		—		1/yr	10	—		—		—	
5.24g		—		—		—		0	10	—		—		—	
5.24h		—		—		—		1/yr	10	—		—		—	
5.24i		—		—		—		1/yr	5	—		—		—	
5.27	Physics & Chemistry	—		—		—		4/yr	30	—		—		—	

Notes: Based on 2-man support module, 30-day maximum on orbit capability
*Payload consists of experiment module, support module, or combination.
†Rate based on a minimum of 3 astronomy modules operating.

Table 2-5. Program Launch Requirements Comparison* — Shuttle-Only

FPE	Title	Number of Launches 5-Day Shuttle Capability	30-Day (Max) Shuttle Capability	Basis
5.1	X-ray	15	15	60 day service
5.2A	Stellar	2	2	60 day service
5.3A-1,-2,-3	Solar	11	11	30 day service
5.4/5.21	UV/IR Survey	1	1	60 day service
5.5	High Energy	8	8	60 day service
5.8	Cosmic Ray	15	15	30 day service
5.9/X	Space Biology	(146)	25	Constant attendance
5.11	Earth Surveys	(73)	26	2-year program
5.6/5.7/5.12	Space/Plasma Physics	25	9	2-year program
5.13/5.14/5.15	Aeromedicine	Not Feasible	13	2-year program
5.16	Materials Science	(77)	18	Blue Book program extended to 3 yr
5.17/5.18	Contamination/Exposure	0	0	Piggy back
5.20-1	Fluid Physics (Attached)	10	2	2-year program
5.20-2,-3,-4	Fluid Physics (Detached)	(42)	24	
5.22	Component Test	(29)	7	2-year program
5.24b,d,e,f,g,h,i	Engineering & Operations	(38)	14	2-year program
5.24c	Engineering & Operations	(23)	15	
5.27	Physics and Chemistry	(40)	8	2-year program

Notes: 5.9X = 5.9/5.10/5.23/5.25/5.26
* Based on 4 yr operations program schedule and 2-man support module
( ) For optional program with restricted number of launches eliminate launches in brackets

Numbers in brackets for a 5-day orbit stay time in Table 2-5 indicate one possible program option where selected FPEs with higher launch requirements are eliminated for cost analysis purposes. The Aeromedicine experiments cannot be accomplished with 5-day stay times since they are basically investigations of the long term effects of the space environment on man. A 30-day stay time support module provides a facility that is attractive for several other experiments that require two scientist-astronauts in attendance.

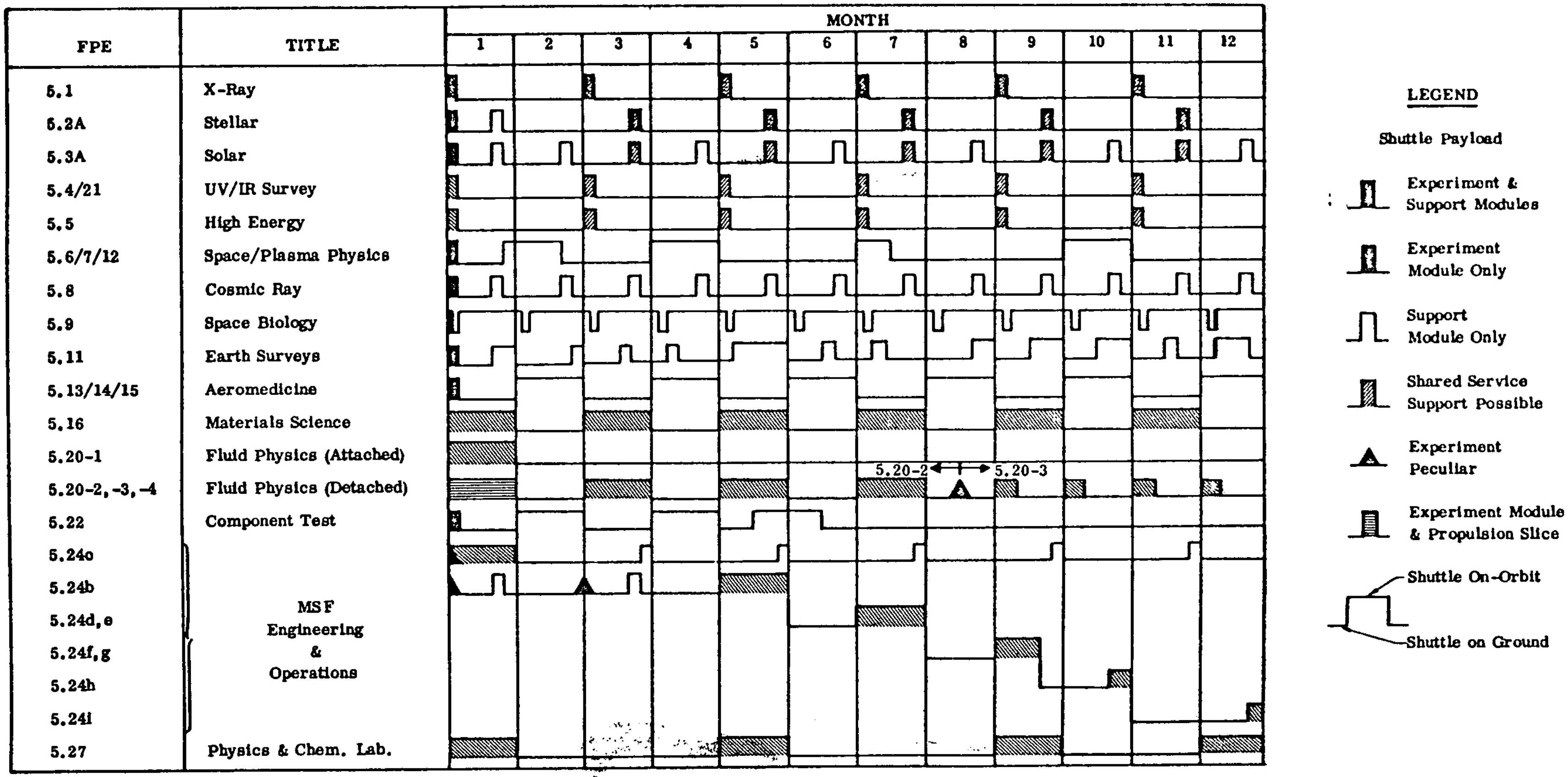
Figure 2-7 summarizes the shuttle payload and launch interval requirements for one year in which all FPEs are in operation. The first year was selected to show the launch requirements for initializing individual experiments. Intervals between launches are nearly minimum but can be extended as desired except for FPEs that are time sensitive such as the slush hydrogen experiment (FPE 5.20-3). Experiment launch requirements of Figure 2-7 should not be added since they are not related to the actual launch sequence.

Figure 2-7 reflects the results of subjecting experiment modules, support modules, combined modules, or experiment-peculiar equipment to launch weight and length constraints to establish the number of launches for initial experiment operation. Experiment and support modules that are either too heavy or too long to be launched together are launched separately and perform orbit maneuvers and rendezvous. Number of launches for experiment initialization is discussed further in Section 2.3.2. FPE 5.1 is typical of combined experiment/support module launches. The experiment module is launched with a support module and subsequently activated. A 60-day interval is required for service; service periods are shared with other astronomy modules during those years when other modules are in operation.

FPE 5.3 is typical of dual initial launches (one launch for the support module and one launch for the experiment module). The Space Biology group of FPEs designated FPE 5.9/X (5.9, 5.10, 5.23, 5.25, 5.26) is an example where back-to-back launches are necessary (e.g., launches with a maximum of 48-hours between support module departure to return to earth and the arrival of the next support module on-orbit) to provide virtually continuous manned attendance. Two support modules and two dedicated shuttles are required with 30-day shuttle on-orbit capability.

FPE 5.11 (Earth Surveys) is typical of missions in the 15 ± 10 days duration. Missions are spaced to measure seasonal phenomena and to be flexible enough to allow for weather uncertainties.

FPE 5.16 (Materials Science), 5.20 (Fluid Physics) and 5.22 (Component Test) are scheduled for a 30-day nominal interval between flights. This interval could be extended or contracted if desired. Scheduled launch intervals require one shuttle or support module for each FPE. Launch intervals for FPEs 5.7 (Plasma Physics) and 5.27 (Physics and Chemistry Laboratory) are scheduled such that a single shuttle and support module can support both FPEs.



First year of operation of each FPE is shown — see launch schedule for program launch sequence.

Figure 2-7. Shuttle Payload and Launch Interval Summary

2.2.4 DUTY CYCLE REQUIREMENTS AND POINTING ACCURACY. An analysis of each FPE for RCS thruster duty cycle requirements and nominal pointing accuracy while attached to the shuttle is shown in Table 2-6. When no specific experiment pointing accuracy was applicable, a ± 5 deg requirement was assumed for experiment servicing and for standby operations such as data evaluation or measurement preparation. A pointing accuracy of 0.5 deg is required for some experiments operating in the attached mode (e.g., FPE 5.11, Earth Survey). Other FPEs (e.g., 5.16, Materials Science) have low-g acceleration constraints. In both situations, experiment module RCS thrusters must be used to either maintain pointing accuracy or to reduce linear acceleration spikes when the RCS thrusters fire.

Based on this data, the following ground rules and derived guidelines, no payload penalties were found to be necessary for on-orbit stabilization of module/shuttle combinations:

a. The orbiter has 2000 lb LH_2/LO_2 available at no penalty for on-orbit stabilization of module/shuttle combinations.

b. Attitude hold outside of experiment duty cycles is ± 5 deg.

c. For pointing accuracies of < ± 1 deg, experiment module RCS is used.

d. For pointing accuracies of > ± 1 deg, shuttle RCS is used.

e. Experiment module propellant scheduled for the space-station-based baseline modules (~ 2500 lb) is available for on-orbit stabilization.

2.3 SHUTTLE-ONLY PROGRAM

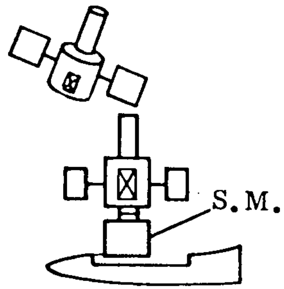
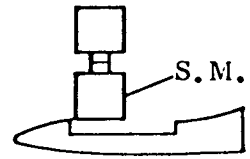
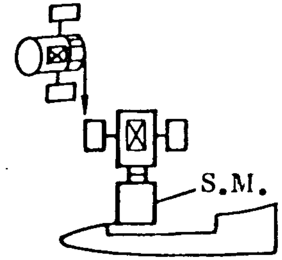
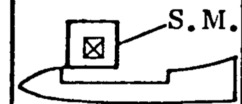
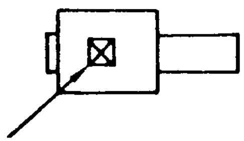
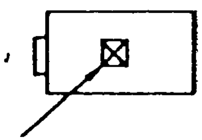
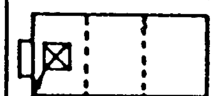
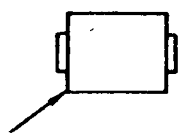
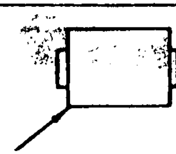
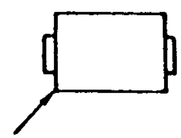
Analysis of the experiment and support requirements for the shuttle-only study has resulted in the assignment of the FPEs to the candidate operations concepts as shown in Figure 2-8. The astronomy experiments and the Cosmic Ray (FPE 5.8) and the Fluid Physics (FPE 5.20 detached mode) are accomplished in mode A. This operational mode requires that a data management kit be incorporated in the experiment modules. The data management kit programs the experiment in the absence of the crew and directs the recording and subsequent transmission of experimental data when interrogated by ground stations. A CM-1 experiment module is required for this mode of operation.

Three experiments are accommodated with operations Concept B — Materials Science (FPE 5.16), Physics and Chemistry Laboratory (FPE 5.27), and the Fluid Physics experiments accomplished in the attached mode (FPE 5.20). The remainder of the experiments are assigned to operations Concept C; Concept D was not found to be useful. Either CM-3 or CM-4 experiment modules can be used with concepts B and C. A dormancy kit is added to the Concept C experiment modules. This kit includes the power, cooling, data management, and operations control equipment necessary to adapt attached modules CM-3 and CM-4 to dormant, free-flight operation.

Table 2-6. Duty Cycles and Pointing Accuracy

FPE	Title	Mode: Service	Mode: Exp. Operations	Mode: Standby	Time (days)	Attached Pointing Accuracy (deg)	Nominal Duty Cycle (% time)
5.1 5.2A 5.3A-1-2-3 5.4/5.21 5.5 5.8 5.20-2, -3, -4	X-Ray Stellar Solar UV/IR Survey High Energy Cosmic Ray Fluid Physics	x			5	±5.0	100% (shuttle)
5.9/x † 5.24c 5.13/5.14/5.15	Space Biology Engineering Operations Aeromedicine		x		30	± 5.0	100% (shuttle)
5.16 5.20-1 5.27	Materials Science Fluid Physics Physics & Chemistry		x		30	±5.0	20% (module) 80% (shuttle)
5.6/5.7/5.12 5.22 5.11*	Space/Plasma Physics Component Test Earth Survey		x	x	30	±0.5 ±5.0	20% (module) 80% (shuttle)
5.24b	Engineering Operations		x		5	±0.5	33% (module)
5.24i				x	5	±5.0	67% (shuttle)
5.24d			x	x	20	±0.5 ±5.0	33% (module) 67% (shuttle)
5.24e 5.24f			x		10	±5.0	100% (shuttle)
5.24h			x	x	5 5	±0.5 ±5.0	33% (module) 67% (shuttle)

Notes: † Active or passive isolation devices may be required to mitigate acceleration spikes
* Capability for truth site pointing for ~50 sites @ 100 deg/min using module and shuttle RCS is also provided.

	A	B	C	D
Operate Concepts Service		 EARTH	 ON-ORBIT OR EARTH	 EARTH
Experiments Applicable	5.1 X-Ray 5.2A Stellar 5.3A Solar 5.4 UV Stellar 5.5 High Energy 5.21 IR Stellar 5.8 Cosmic Ray 5.20-2 Fluid Phy.	5.16 Matl. Science 5.20-1 Fl. Phys. 5.24 Eng. Oper. (Part) 5.27 Phys. & Chem.	5.6 Space Physics 5.7/5.12 Plasma 5.9/X Biology 5.11 Earth Surveys 5.13/14/15 Aeromedicine 5.22 Compl Test 5.24 Eng. Oper. (Part)	Not Used
Experiment Module	 Data Mgt. Kit CM-1	 CM-3 or CM-4	 Dormancy Kit CM-3 or CM-4	 Crew Habit-ability Kit CM-4
Space Station Substitute Items	 Support Module	 Support Module	 Support Module	—

5.9X ≡ 5.9, 5.10, 5.23, 5.25, 5.26

Figure 2-8. Summary of Concept Applications & Substitutes Shuttle-Only Study

2.3.1 EXPERIMENT IMPLEMENTATION SUMMARY. The selected method of implementing the various experiments is summarized in Table 2-7. This table identifies the operations concept, common module type, and the desired on-orbit stay time for each FPE.

Experiment module changes (from the baseline space station based concept) are divided into two parts — changes in kit form, and other changes. A data management kit is required for each of the free-flying modules (Concept A); and a dormancy kit is required for each of the modules left on-orbit in a dormant mode (Concept C). The other changes include the cases where experiments previously assigned to the space station require a new module assignment for the shuttle-only study, and one case where an experiment (FPE 5.8 — Cosmic Ray), which was conducted in the attached mode for the baseline experiment program, has been reassigned to a free-flying module. The reassignment was made because of the desired long term experiment duration. The inclusion of the Space Physics experiment (FPE 5.6) with the FPE 5.7 experiment module requires that the FPE 5.7 module be modified to include scientific airlocks. These airlocks are also available for those FPE 5.17 experiments which require airlocks.

The Experiment Support columns indicate the primary reason for crew support and the primary source of electrical power and experiment module stability and control (S&C). The experiment crew services the experiments while on-orbit and in a large number of instances actively conducts the experiments. Experiments, which draw their power from the space station for the baseline program, largely draw their power from the support module in the shuttle-only study. Stability and control functions are mainly provided by the orbiter when the modules are docked to the support module and from the modules themselves when they are in free-flight. Several FPEs operating in the attached mode have stability and control requirements or low-g acceleration constraints which cannot be attained with the orbiter RCS thruster — in these cases, the experiment module RCS thrusters are used to control the orbiter/module configuration. The Space Physics (FPE 5.6) Contamination (FPE 5.17), and Component Test (FPE 5.22) experiments have several sub-experiments which require that additional, experiment-peculiar, stability and control be provided. Modules operating in the dormant mode also have a stability and control requirement which the experiment modules must provide during these periods.

2.3.2 EXPERIMENT OPERATIONS. Methods of accomplishing the candidate experiment program are described in the following paragraphs. All orbits described in these paragraphs are circular orbits.

2.3.2.1 FPE 5.1 — Grazing Incidence X-Ray Telescope. The astronomy experiments, FPEs 5.1, 5.2A, 5.3, 5.4, 5.5, and 5.21 are accomplished in similar ways. This method is described in detail here for FPE 5.1 and referenced for the other astronomy experiments.

An experiment module and a support module are delivered to an interim orbit (150 n.mi. at an inclination of 55 deg for FPE 5.1). Initial activation of the experiment module is

Table 2-7. Experiment Implementation Summary (Shuttle Only)

FPE		Operations Concept	Common Module	Desired Staytime	XMod Changes		Experiment Support			Comments
					Kit	Other	Crew	Power	Stab. & Contr.	
5.1	X-Ray	A	CM-1	Cont.	Data Mgt.	–	Service	XMod	XMod & Orbiter	
5.2A	Stellar	A	CM-1	Cont.	Data Mgt.	–	Service	XMod	XMod & Orbiter	
5.3A	Solar	A	CM-1	Cont.	Data Mgt.	–	Service	XMod	XMod & Orbiter	
5.4	UV Survey	A	CM-1	Cont.	Data Mgt.		Service	XMod	XMod & Orbiter	Not in baseline, includes 5.21
5.5	High Energy	A	CM-1	Cont.	Data Mgt.	–	Service	XMod	XMod & Orbiter	
5.6	Space Physics	C	CM-3	5 days	Data Mgt.	New	Operate	Suppt. Mod.	XMod & Orbiter + Experiment	Combine with FPE 5.7, add airlock to 5.7, not in baseline
5.7	Plasma Physics	C	CM-3	30 days	Data Mgt.	–	Operate	Suppt. Mod.	XMod & Orbiter	Includes FPE 5.6 & 5.12
5.8	Cosmic Ray	A	CM-1	Cont.	Data Mgt.	To CM-1	Operate	XMod	XMod & Orbiter	Changed to free-flying module
5.9	Vertebrates	C	CM-3	30 days	Dormancy	–	Operate	X & Suppt. Mod.	XMod & Orbiter	+ centrifuge, back-to-back servicing with < 48 hour gap, includes 5.10/23/25/26
5.10	Plants	C	CM-3	30 days	Dormancy	–	Operate	X & Suppt. Mod.	XMod & Orbiter	See FPE 5.9
5.11	Earth Surveys	C	CM-4	30 days	Dormancy	–	Operate	Suppt. Mod.	XMod & Orbiter	
5.12	RMS	C	CM-3	30 days	Dormancy	–	Operate	XMod	XMod & Orbiter	Combine with FPE 5.7
5.13	Aeromedicine	C	CM-4	30 days	Dormancy	New	Operate	Suppt. Mod.	XMod & Orbiter	+ centrifuge, includes FPE 5.14 & 5.15, not in baseline.
5.14	Man/System	C	CM-4	30 days	Dormancy	New	Operate	Suppt. Mod.	XMod & Orbiter	See FPE 5.13
5.15	Life Support	C	CM-4	30 days	Dormancy	New	Operate	Suppt. Mod.	XMod & Orbiter	See FPE 5.13
5.16	Materials Science	B	CM-3	30 days	–	–	Operate	Suppt. Mod.	XMod & Orbiter	
5.17	Contamination	Suitcase	–	Varies	–	–	Service	X & Suppt. Mod.	XMod & Orbiter + Experiment	Experiments ride piggy-back with both attached & free-flying modules, varying experiment times up to two years.
5.18	Exposure	Suitcase	–	Varies	–	–	Service	X & Suppt. Mod.	–	Same as FPE 5.17
5.19	Space Structure									Deleted from program.
5.20	Fluid Physics	A & B	CM-3 & -1	30 days	Data Mgt.	–	Service	X & Suppt. Mod.	XMod & Orbiter	Two modules used with propulsion slice
5.21	IR Survey	A	CM-1	Cont.	Data Mgt.	New	Service	XMod.	XMod & Orbiter	See FPE 5.4
5.22	Component Test	C	CM-4	30 days	Dormancy	–	Operate	X & Suppt. Mod.	XMod & Orbiter	Option for 5 day staytime with increased flights
5.23	Primates	C	CM-3	30 days	Dormancy	–	Operate	X & Suppt. Mod.	XMod & Orbiter	See FPE 5.9
5.24	Engr. & Oprs. (except C)	B & C	CM-3	20 days	Dormancy	New	Operate	X & Suppt. Mod.	XMod & Orbiter	FPE 5.24a not possible, not in baseline, 3 crewmen for 5.24e (EVA)
5.24c	Engr. & Oprs.	C	CM-4	30 days	Dormancy	New	Service	XMod	XMod & Orbiter	
5.25	Microbiology	C	CM-3	30 days	Dormancy	–	Operate	X & Suppt. Mod.	XMod & Orbiter	See FPE 5.9
5.26	Invertebrates	C	CM-3	30 days	Dormancy	–	Operate	X & Suppt. Mod.	XMod & Orbiter	See FPE 5.9
5.27	Phys. & Chem. Lab	B	CM-3	30 days	–	–	Operate	Suppt. Mod	XMod & Orbiter	10^{-6} & sustained G experiments conducted in detached module

FOLDOUT FRAME

FOLDOUT FRAME 2

accomplished by the experiment crew in this orbit. The experiment module is then undocked from the support module and a Hohmann transfer propelled by the experiment module's RCS thrusters brings the module to the desired 270 n.mi. circular orbit. The data recording phase of the mission then starts. Less than 1500 lb of propellant are used to deliver the module to its operating orbit. However, the module's propellant load will have to be replenished soon — probably on the first shuttle trip for servicing following the initial boost.

Servicing is accomplished at 30- or 60-day intervals (60 days for FPE 5.1). Up to three experiment modules may be serviced with a single shuttle flight of five days duration. Experiment service activities consist of cryogenic replenishment, film removal and replacement, and planned maintenance tasks. Experiment update is accomplished at a nominal interval of once per year. Two men are required for module servicing; however, a four man crew is desirable if concurrent service and EVA activities are planned.

A typical cycle for servicing a single experiment module is shown in Table 2-8; 19.8 hours are required. Three modules can then be serviced in a single five-day shuttle flight as shown in Figure 2-9. Separate timelines are shown for crewman A and crewman B. During the first working day, module number 1 is brought to the support module, docked, and servicing accomplished through Task 7 of Table 2-8. On the second day, servicing of module number 1 is completed; the shuttle then transfers to module number 2, and module 2 servicing tasks are completed through Task 5. This procedure continues through the fifth day when servicing of the third module is completed and the crew returns to earth.

The three modules are traveling in nearly identical orbits (orbits need not be exactly co-planar or co-altitude) with less than 4.7 n.mi. separation between the extreme modules of the group as shown in Figure 2-10. This separation distance is fixed by the ground data station receiving antenna beam width of one degree. The receiving antenna slews to lock on to the modules as they rise over the antenna horizon and tracks the modules for 11 minutes until they pass beneath the antenna horizon on the far side. Data recorded during the prior orbit is transmitted to the ground station during this 11-minute period. A second group of experiment modules can follow at an interval of not less than 13 minutes (11 minutes tracking plus two minutes for slewing the antenna to the next group of modules). Data transfer operations are described in greater detail in Section 3.6

Figure 2-9 timelines represent tasks 4 through 13 of Table 2-8. Prior and later tasks are under the control of ground stations and do not require the attention of the experiment module crew. The total service cycle time of 19.8 hours from Table 2-8 does, however, show the experiment time lost. Following completion of the final manned servicing task (Task 13), the orbiter transfers, in a single orbit, to rendezvous with the next experiment module, and another service cycle is started.

Table 2-8. Typical Astronomy Servicing Cycle — Shuttle-Only

Task No.	Task Description	Number of Crew	Control Mode*	Time Required (hr)**	Elapsed Time (hr)
1	Secure experiment equipment	0	GR	0.25	0.25
2	Ready module subsystems for return	0	GR	0.25	0.50
3	Orient module and apply transfer ΔV impulse	0	GR	0.25	0.75
4	Rendezvous with shuttle and dock	1	R	0.4	1.15
5	Pressurize module and leak test	1	R	2.0	3.15
6	Open hatch and inspect module	2	M	0.5	3.65
7	Service experiments*	2	M	6.0	9.65
8	Service module subsystems*	2	M	2.0	11.65
9	Inspect module	2	M	0.5	12.15
10	Close hatch and depressurize	1	M	4.0	16.15
11	Checkout experiments and module subsystems	1	R	1.0	17.15
12	Ready module subsystems for launch	1	R	0.5	17.65
13	Launch module and clear shuttle buffer zone	1	R	0.15	17.82
14	Orient module and apply transfer ΔV impulse	0	GR	0.25	18.07
15	Acquire pointing reference	0	GR	0.25	18.30
16	Orient module	0	GR	0.25	18.55
17	Ready module subsystems for experiments	0	GR	0.25	18.80
18	Ready experiment equipment	0	GR	0.5	19.30
19	Resume observation program	0	GR	0.5	19.80

* Control Modes: GR = Ground Remote, R = Orbital Remote, M = Manual.

**Servicing times will vary with individual modules; typical values are shown for replenishment of expendables, adjustments and calibration, and do not include repair time.

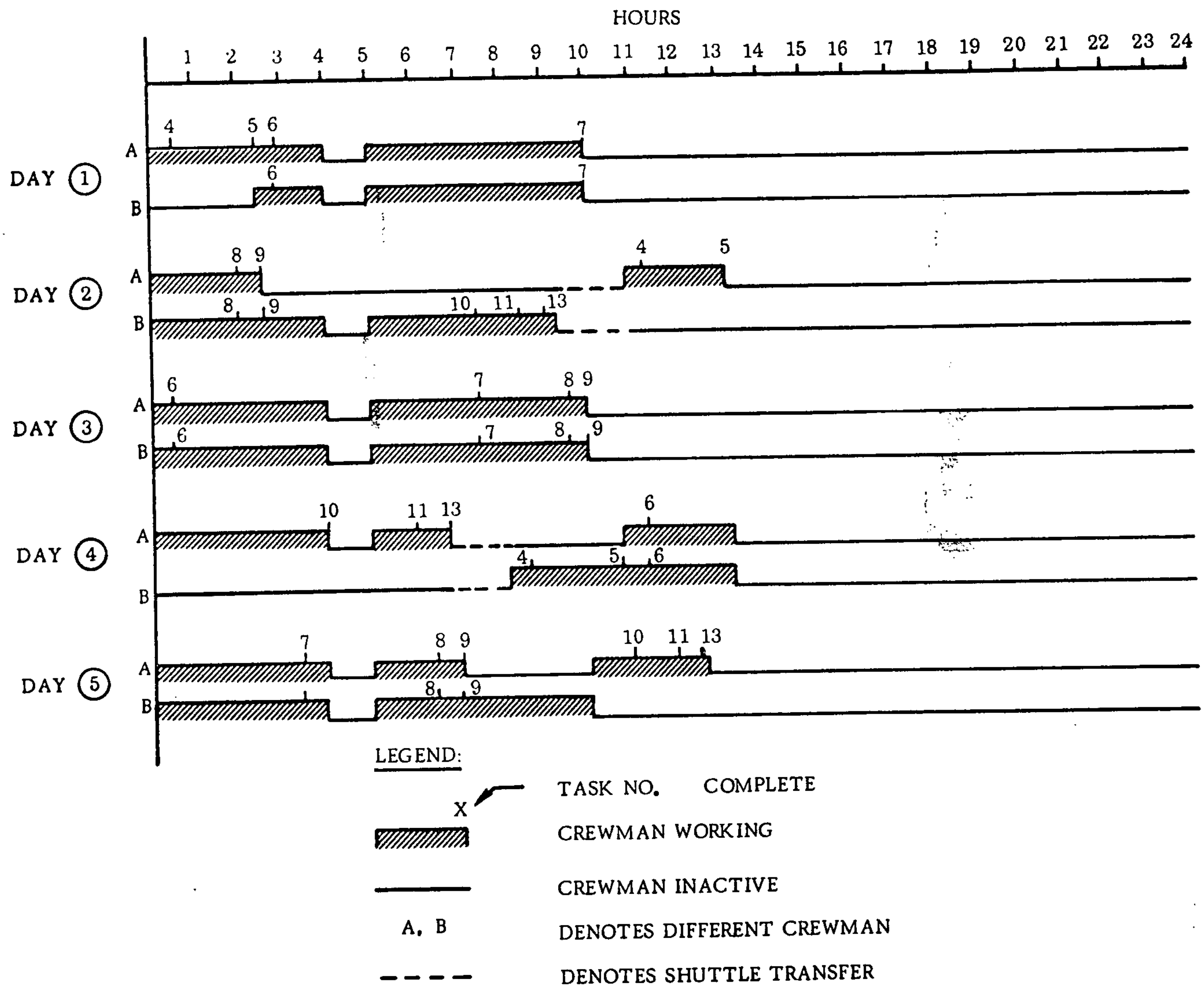


Figure 2-9. Astronomy Module Service Timeline — Shuttle-Only

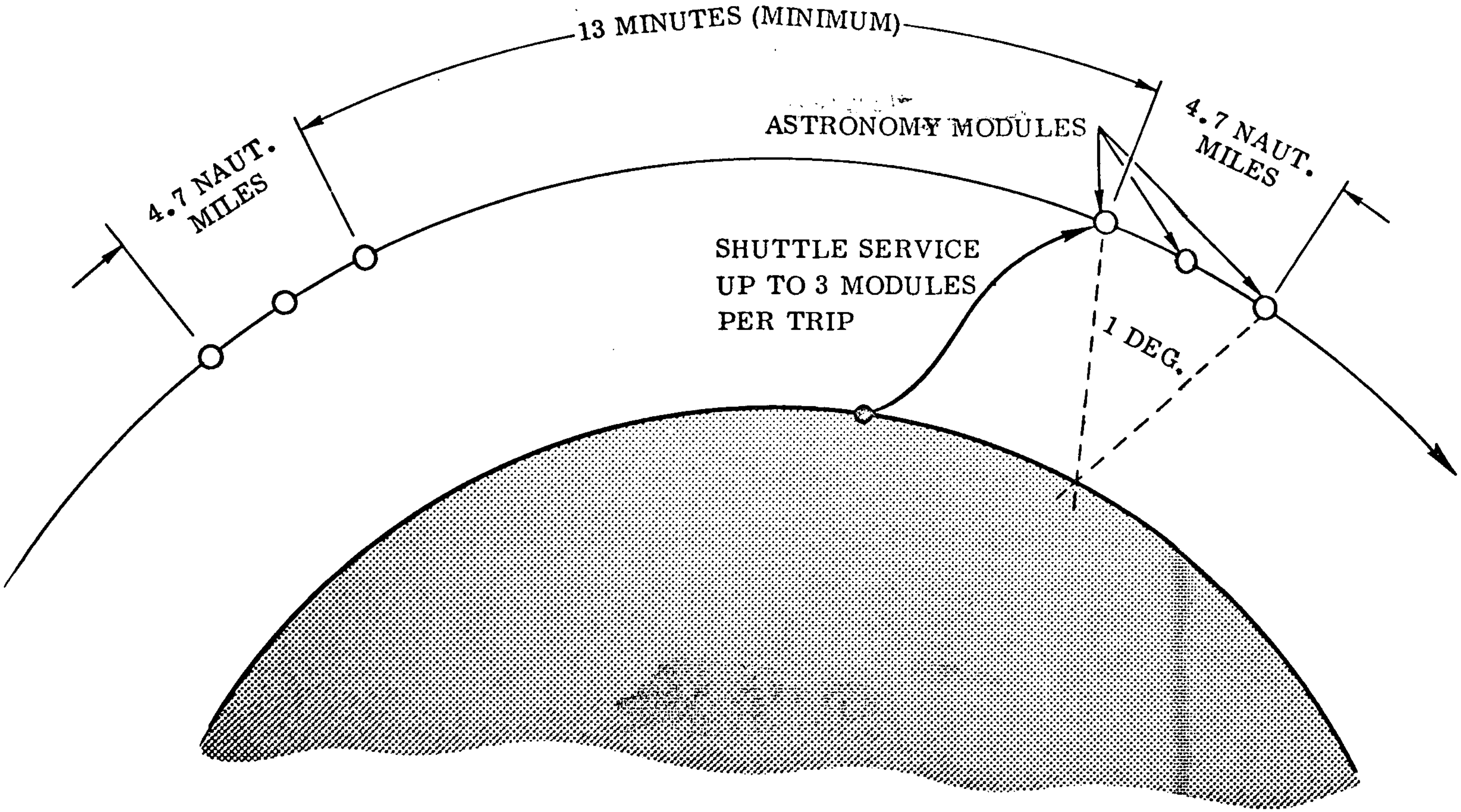


Figure 2-10. Astronomy Module Operations — Shuttle-Only

2.3.2.2 FPE 5.2A — Stellar Astronomy Module. The weight of the experiment module for this FPE plus the weight of the support module exceeds the capability of the shuttle to deliver this combination to an orbit altitude from which the experiment module can then power its way to the desired 270 n.mi. orbit. Two shuttle boosts are therefore required to initiate this experiment.

The experiment module is delivered to a nominal 175 n.mi. at 55 deg inclination orbit by the shuttle. No support module is boosted on this shuttle flight. The shuttle is undocked from the module, and the module then executes a Hohmann transfer to 270 n.mi. using its own RCS. The module is then placed in a free-flying but dormant (stationkeeping only) status while the shuttle returns to the ground. A second shuttle flight boosts the experiment crew and a support module to orbit. The free-flying module then docks to the support module for initial activation. Following activation it is deployed for unmanned operation under ground control.

2.3.2.3 FPE 5.3A — Solar Astronomy Module. The total FPE 5.3A experiment is contained in a single experiment module. Payload capability of the shuttle is exceeded by the combined experiment and support module weights. Two launches are therefore used to activate this experiment. On the first launch the experiment module is carried to 175 n.mi., 55 deg inclination orbit. The orbiter is undocked from the module and the module executes a Hohmann transfer to 270 n.mi. using its own RCS. The module is then placed in free-flying but dormant status while the shuttle returns to the ground. The second shuttle flight boosts the experiment crew and a support module to the 270 n.mi. orbit. The dormant experiment module then docks to the support module for initial activation.

2.3.2.4 FPE 5.4 — UV Stellar Survey. This experiment and FPE 5.21 (Infrared Stellar Survey) are combined in the same module. These are experiments which had been assigned to the space station in the space-station-based experiment module program. The operations scheme follows the typical example described in Section 2.3.2.1. Scheduled module service occurs at 60-day intervals.

2.3.2.5 FPE 5.5 — High Energy Stellar Astronomy. Combined experiment and support module weights again exceed shuttle payload capability. The experiment module is boosted by itself to a 270 n.mi. orbit at an inclination of 55 deg. A second shuttle flight carries a support module and the crew to activate the experiment to the 270 n.mi. orbit. The experiment module docks to the support module; the experiment is activated, and subsequently the module undocks and starts recording data. Scheduled module service is performed at 60-day intervals.

2.3.2.6 FPE 5.6 — Space Physics Airlock Experiments. Each of the several parts to this experiment is carried piggy-back on the FPE 5.7 module. Scientific airlocks are incorporated into the module to accommodate these experiments. This is a new experiment for the shuttle-only study.

2.3.2.7 FPE 5.7 — Plasma Physics and Environmental Perturbations. FPE 5.6 (Airlock) and 5.12 (RMS) and portions of FPE 5.17 (Contamination) are accomplished with the experiment module assigned to this FPE. This experiment requires lengthy manned operations approaching a 30-day on-orbit stay time — particularly early in the program when antennas are erected, maneuverable subsatellites deployed, and diagnostic measurements of the plasma field made for calibration purposes. The combined weight of the experiment and support modules exceeds the shuttle payload capability (minimum requirements are 200 n.mi. at 55 deg inclination). Therefore, the experiment module is delivered separately to a 270 n.mi. (or slightly less depending on the final experiment module weight) orbit at 55 deg and following undocking from the orbiter is placed in the dormant state. A second shuttle launch brings up a support module and a crew to activate the experiments and to conduct the initial measurements. The experiment module is manned during all experiment periods and left on-orbit in the dormant state when the crew returns to earth.

There are six distinct experiments grouped in FPE 5.7. It is ultimately desired that this experiment measure the plasma field and how it interacts with natural and induced environments for the range of day/night, geographical, seasonal, and cyclic parameters.

2.3.2.8 FPE 5.8 — Cosmic Ray Physics Laboratory. The weight of this experiment module far exceeds shuttle payload capability at 55 deg inclination orbit. To obtain a reasonable operating altitude the experiment must be accomplished at an inclination near 28.5 deg. The shuttle boosts the experiment module to an orbit altitude of approximately 200 n.mi. at 28.5 deg inclination. From this orbit the experiment module then executes a Hohmann transfer using its RCS engines to a circular orbit altitude of 270 n.mi. The module remains in a dormant status at this altitude until a second shuttle launch brings a support module and an experiment crew to activate the experiment. Module service requiring five days is accomplished at 30-day intervals.

2.3.2.9 FPE 5.9 — Small Vertebrates (Bio D). All of the biology experiments (FPE 5.9/10/23/25 and 26) are contained within a single experiment module. These experiments require nearly continuous attention by an experiment crew — an unattended period of 48 hours between back-to-back shuttle flights is assumed.

This experiment is both too heavy and too long (exceeds shuttle cargo bay length when combined with a support module) to be boosted with a support module. The experiment module (only) can be boosted by the shuttle to about a 150 n.mi. orbit at a 55 deg inclination angle. A subsequent Hohmann transfer of the experiment module only powered by its RCS brings the module to a 230 to 240 n.mi. altitude where it rendezvous with a previously launched orbiter/support module/experiment crew. A 270 n.mi. circular orbit can be obtained at a 28.5 deg inclination angle using the same type of technique as described for the 55 deg inclination orbit.

2.3.2.10 FPE 5.10 — Plant Specimens (Bio E). This experiment is accomplished with FPE 5.9. See Section 2.3.2.9.

2.3.2.11 FPE 5.11 — Earth Surveys. This experiment module is both too long and too heavy to be boosted simultaneously with the support module. The experiment module is boosted separately to a 270 n.mi. orbit at 55 deg inclination. A second shuttle launch carries a support module and the experiment crew to this orbit; following docking of the experiment module to the support module the experiments are activated and the initial series of measurements accomplished. Experiments are manned for periods up to 30 days with the sensors operating for approximately 15 minutes per orbit. When the experiment module is undocked from the support module, the experiment module is placed in a dormant status until the next crew arrives to once again man the experiments.

2.3.2.12 FPE 5.12 — Remote Maneuvering Subsatellite. This experiment is accomplished with FPE 5.7. See Section 2.3.2.7.

2.3.2.13 FPE 5.13 — Biomedical and Behavioral Research. Three FPEs (5.13, 5.14 and 5.15) are accomplished housed within a single experiment module. All of these experiments are new to the experiment module program with the shuttle-only study. These experiments are investigations of the long duration effects of space environment on man. Experiment duration is limited to 30 days by the shuttle-only ground rules. Portions of these experiments require a minimum crew of four, and, as such, cannot be accomplished with the baseline support module (limited to a crew of two). However, it is possible to design a four-man support module at increased weight and cost. This analysis is based on the use of such a module.

This experiment module is too long to be boosted with the support module. It is boosted separately by the shuttle to about a 200 n.mi. orbit at 55 deg. A Hohmann transfer can then be accomplished by the experiment module using its own RCS to an altitude of 270 n.mi. A second shuttle launch brings a support module and the experiment crew to the experiment module orbit where the experiment module docks to the support module. All experiments are manned and some are conducted for periods up to 30 days. When the crew returns to earth the experiment module is left on-orbit in a dormant state.

2.3.2.14 FPE 5.15 — Man/System Integration. This experiment is accomplished with FPE 5.13. See Section 2.3.2.13.

2.3.2.15 FPE 5.15 — Life Support and Protective Systems. This experiment is accomplished with FPE 5.13/14. See Section 2.3.2.13.

2.3.2.16 FPE 5.16 — Materials Science and Processing. This experiment module and a support module are boosted together by the shuttle to approximately a 250 n.mi. orbit at a 28.5 deg inclination. The experiment crew then activates the experiments and conducts measurement programs for up to 30 days on orbit. The experiment module is returned to earth following each experiment period.

2.3.2.17 FPE 5.17 — Contamination Measurements. These are suitcase experiments which are carried to orbit on experiment modules dedicated to other FPEs. Only periodic manned attendance is required for these experiments, but some EVA operations are necessary to retrieve experimentation samples fastened to the exterior of the experiment modules. Those experiments requiring scientific airlocks are assigned to the FPE 5.7 (Plasma Physics) module.

2.3.2.18 FPE 5.18 — Exposure Experiments. These experiments are also suitcase experiments which are carried to orbit on experiment modules dedicated to other FPEs. EVA operations are necessary for this experiment.

2.3.2.19 FPE 5.19 — Extended Space Structure Development. This FPE has been deleted.

2.3.2.20 FPE 5.20 — Fluid Physics in Microgravity. There are four parts to this FPE, -1 through -4, FPE 5.20-1 experiments are accomplished with the experiment module attached to the support module (which is, in turn, attached to the orbiter). The experiment and support modules are boosted together by the shuttle to a 210 n.mi. orbit at an inclination of 55 deg. If higher altitudes are desired, the orbit altitude can be increased to 270 n.mi. at 28.5 deg inclination. Manned experiments are conducted for up to 30 days, and the experiment module is returned to earth with the orbiter at the conclusion of each FPE 5.20-1 experiment period.

FPE 5.20-2, -3, and -4 require lengthy test periods at sustained, low-g levels. These sustained g levels are supplied by a propulsion slice in the space station based experiment module program. It is possible that some of the test conditions could be attained by using the orbiter's drag deceleration during a shuttle-only program. This is an alternative operating mode which holds promise of reducing the cost of conducting these experiments. However, further investigation is necessary to establish its feasibility. The operating mode described here parallels the previously defined space station based mode of operations.

Two shuttle flights are required to initiate experiment phases -2 and -3. The first shuttle flight delivers a CM-1 experiment module and a propulsion slice to a 270 n.mi. x 28.5 deg orbit or alternatively to a 210 n.mi. x 55 deg orbit. The module undocks from the orbiter and remains on-orbit in a dormant state while the shuttle returns to earth. The second shuttle launch brings a CM-3 module, a support module and the experiment crew to orbit. The CM-1 module with the propulsion slice then docks to the CM-3 module and the experiment is activated. The CM-1 module and the propulsion slice then undock and the sustained low-g flight program begins. An automatic control system on-board the CM-1 module directs the flight profile during free-flight. The crew remains on-orbit for from 5 to 30 days to monitor, service and replenish propellants. At the conclusion of each experimentation period, the CM-1 module is left in a dormant state while the CM-3 and support modules are returned to earth. FPE 5.20-2 is divided into several phases with additional propellants for each phase brought to orbit in the support module.

Propellants are transferred through the CM-3 module to the propulsion slice as required. When the -2 experiment is completed the CM-1 module and the propulsion slice are left on-orbit in a dormant state while the CM-3 and the support modules are returned to earth.

The -3 experiment starts with a support module and a slush hydrogen tank being boosted to orbit where the CM-1 module is activated and docks to the test tank. The test tank is then undocked and remains on-orbit with the CM-1 module while the support module is returned to earth. A second shuttle flight brings a CM-3 module and a support module to orbit. The CM-1 module with the propulsion slice and the slush hydrogen test tank dock to the CM-3 module and the experiment is updated and activated. Sustained low-g experiments are then conducted with the CM-1/propulsion slice/slush hydrogen tank in free-flight. Replenishment propellants are brought to orbit in the support module. At the conclusion of this experiment the test tank is docked to the support module and returned to earth. The CM-1 and the CM-3 modules remain on-orbit in a dormant state.

The -4 experiment starts with the delivery of a support module and a new task tank to orbit. The CM-1 module docks with the test tank and undocks it from the support module. This is followed by docking of the CM-3 module to the support module and docking of the CM-1/propulsion slice/test tank combination to the CM-3 module. The experiment is then updated and activated and the free-flight low-g experiments accomplished.

2.3.2.21 FPE 5.21 — Infrared Stellar Survey. This experiment is accomplished with FPE 5.4. See Section 2.3.2.4.

2.3.2.22 FPE 5.22 — Component Test and Sensor Calibration. Since this experiment module is too long to be boosted to orbit with a support module, two shuttle launches are required to initiate this FPE. The first launch carries the experiment module to a 270 n.mi. by 55 deg inclination orbit. The second launch carries the experiment crew and the support module to orbit where the experiment module docks to the support module. Manned experiments of up to 30 days duration are completed, and long duration experiments are initiated. The long duration experiments continue while the experiment module is left in a dormant state after the crew returns to earth.

2.3.2.23 FPE 5.23 — Primates (Bio A). This experiment is accomplished with the Space Biology group of experiments. See Section 2.3.2.9.

2.3.2.24 FPE 5.24 — MSF Engineering and Operations. There are nine major subdivisions to this FPE — 5.24a through 5.24i. FPE 5.24a cannot be accomplished in the shuttle-only program as the experiment is presently described. A hangar is called for with physical dimensions in excess of the shuttle cargo bay capability. However, it is possible that the intent of FPE 5.24a could be accomplished with the Remote Maneuvering Subsatellite hangar module defined for FPE 5.7/12.

FPE 5.24b (experiments B and C), d, e, f, g, h, and i are accomplished using a single experiment module which is retrofitted for the various experiments. These experiments are not inclination angle critical. Experiment and support modules can therefore be boosted with a single shuttle flight to a 250 n.mi. orbit at 28.5 deg inclination. Experiment times are short (up to 10 days) and the experiment module is returned to the ground following each experiment.

FPE 5.24b.A consists of a large (37,000 lb) experiment package for investigating control of rotating spacecraft. The experiment package contains an attitude control system and guidance and navigation equipment. Two shuttle launches are required for this experiment. Shuttle launch number one carries the experiment package to 220 n.mi. orbit at a 28.5 deg inclination. The second launch brings the support module to the same orbit where the module and the experiment are mated. This experiment requires a five-day stay time. At the conclusion of the experiment, the experiment package can either be left in orbit or it can be returned to earth with the support module.

FPE 5.24c consists of long duration engineering and development tests of a Brayton cycle isotope power system. The dual 7.5 kW power systems recommended in the Blue Book cannot be packaged within orbiter cargo bay dimensions. A single 7.5 kW power system can be packaged in a 15 x60 ft cylinder. This experiment-peculiar package must be boosted separately to orbit because of its extreme length. An experiment module, which when on-orbit will provide stability and control and stationkeeping functions to the experiment package, is boosted to a 250 n.mi. x 28.5 deg orbit with an experiment crew and a support module on the first shuttle flight. The second shuttle launch carries the experiment package to orbit where the experiment module undocks; transfers to the second shuttle; docks to experiment package; and returns with the experiment package to the support module.

The second shuttle returns to earth; the experiment is activated and developmental tests conducted. Then the experiment module and package are undocked for several months of space qualification and operational tests. During this period the experiment module provides stabilization for the experiment package. The crew is returned to the earth. Service trips to orbit are accomplished at approximately 60 to 180 day intervals to service the experiment and replenish experiment module consumables.

2.3.2.25 FPE 5.25 — Microbiology (Bio C). This experiment is accomplished with the Biology group of experiments. See Section 2.3.2.9.

2.3.2.26 FPE 5.26 — Invertebrates (Bio F). This experiment is accomplished with the Biology group. See Section 2.3.2.9.

2.3.2.27 FPE 5.27 — Physics and Chemistry Laboratory. These experiments are not sensitive to orbit inclination. Both the experiment and shuttle modules are boosted on a single shuttle flight to a 240 n.mi. x 28.5 deg orbit. Sustained low-g acceleration tests are conducted in the FPE 5.20-2 module. Attached module experiments are conducted on-orbit for up to 30 days and both modules are returned with the crew by the shuttle orbiter at the conclusion of the experiment period.

2.3.3 FOUR YEAR OPERATIONS PLAN. A preliminary four year baseline operations plan is shown in Figure 2-11. The plan covers calendar years 1977 through 1981 and ends when the space station is available to support experiment module operations. The launch spacing and sequence is based on the baseline experiment module program launch schedule. However, for shuttle-only, additional FPEs are considered and the total program time period is reduced from 4-1/2 years to comply with the ground ruled four-year shuttle-only program duration.

The operations plan reflects an assumption that astronomy modules will operate from the time they are flight-available until the end of the four-year period. The other FPEs are shown as operating over a two year period excepting FPE 5.16 — Materials Science and Processing. In some cases, the Blue Book program consumes the whole two year period such as FPE 5.20 — Fluid Physics. Other FPEs may be accomplished in one year or less, but typical programs are assumed to be repeated in the second year. FPEs in this class are 5.11 — Earth Surveys, 5.6 — Space Physics, 5.13/14/15 — Aeromedicine, 5.22 — Component Test and Sensor Calibration, MSF Engineering and Operations (excepting the Brayton isotope power system), and 5.27 — Physics and Chemistry. Materials Science and Processing, FPE 5.16, is shown with the Blue Book two year program extended to a three year period. By using a minimum launch interval of 30 days, back-to-back shuttle flights are avoided and extra time is provided for ground analysis and evaluation of experiment data.

2.4 PROGRAM FEASIBILITY

Program feasibility is assessed from two standpoints: (1) can the experiment be boosted to orbit and serviced while in orbit, and (2) can experiment requirements be met once the experiment is on orbit. Table 2-9 summarizes the results of the assessment of boost and servicing feasibility. All of the FPEs are capable of boost to orbit and servicing on-orbit with the exception of FPE 5.24a, which calls for a space hangar that exceeds the shuttle cargo bay dimensions. It is possible, however, that the intent of this FPE can be accomplished with the Remote Maneuvering Subsatellite hangar, FPE 5.12.

All experiment acceleration, stability, viewing, contamination and radiation on-orbit requirements can be met with a shuttle-only program, subject to the following possible exceptions:

a. Acceleration levels may be exceeded for FPEs 5.10 (Plant Speciments), 5.16 (Materials Science), 5.20 (Fluid Physics), 5.25 (Microbiology) and 5.27 (Physics and Chemistry Laboratory) unless experiment peculiar vibration isolators are used.

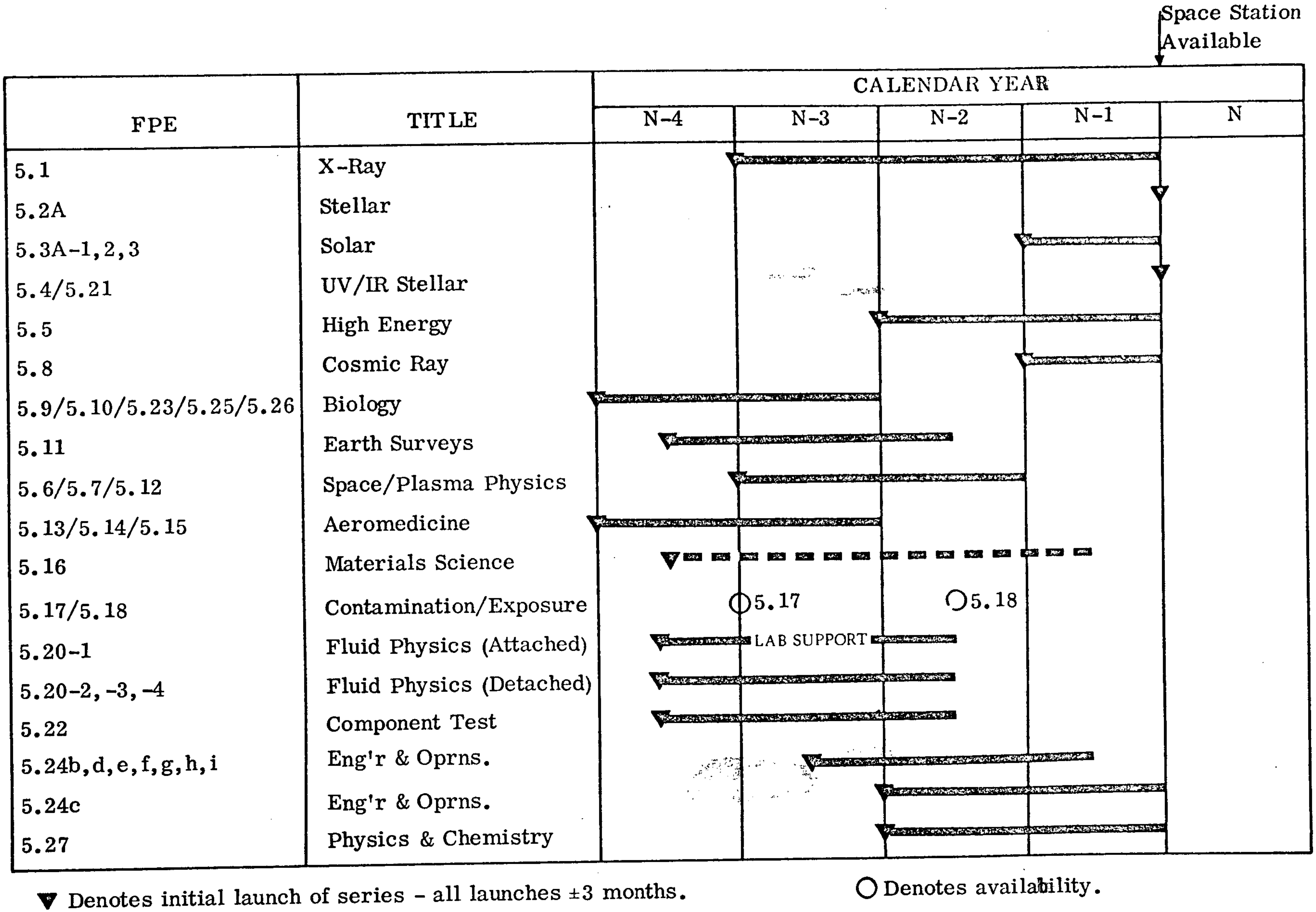


Figure 2-11. Preliminary Four-Year Baseline Operations Program

Table 2-9. Summary of Boost and Servicing Feasibility

FPE	Title	Length (ft)		Weight (lb)		Orbit (n.mi./deg. incl.)		Experiment & Support Mods. Launched	
		XMod	XMod + Suppt Mod	XMod	XMod + Suppt Mod	Preferred	Obtainable	Together	Separately
5.1	X-Ray	40.7	60.0	21,195	32,970	270/55	270/55	x	
5.2A	Stellar	57.3	(76.6)	29,629	(41,424)	270/55	270/55		x
5.3A	Solar	54.4	(73.8)	27,792	(39,587)	270/55	270/55		x
5.4/21	UV/IR Stellar	24.0	43.3	22,945	34,740	270/55	270/55	x	
5.5	High Energy	24.0	43.3	24,544	(36,339)	270/55	270/55		x
5.6/7/12	Space/Plasma Phys.	32.0	51.3	25,990	(42,290)	270/55	270/55		x
5.8	Cosmic Ray	25.6	44.9	36,950	(48,745)	270/55	270/28.5		x
5.9/x	Space Biology	44.8	(64.1)	34,062	(50,352)	270/55	240/55		x
5.11	Earth Surveys	43.0	(62.3)	25,143	(41,443)	270/55	270/55		x
5.13/14/15	Aeromedicine	55.8	(75.1)	30,352	(50,827)	270/55	270/55		x
5.16	Materials Science	23.0	42.3	18,671	34,971	270/55	250/28.5	x	
5.17	Contamination	Suitcase	Suitcase	Suitcase	Suitcase	270/55	270/55	–	–
5.18	Exposure	Suitcase	Suitcase	Suitcase	Suitcase	270/55	270/55	–	–
5.20	Fluid Physics	23.0	42.3	14,066	30,366	270/55	210/55	x	
5.22	Component Test	42.0	(61.3)	21,579	(37,879)	270/55	270/55		x
5.24c	Engr. & Ops.	34.0	53.3	17,475	33,775	270/55	250/28.5	x	
5.24*	Engr. & Ops.	23.0	42.3	18,800	35,100	270/55	250/28.5	x	
5.27	Phys. & Chem.	23.0	42.3	20,501	36,801	270/55	240/28.5	x	

( ) Indicates parameter exceeds shuttle capability - either cargo bay length or payload capability to 270 n.mi./55 deg orbit.

5.9/x ≡ 5.9, 5.10, 5.23, 5.25, 5.26

5.24* ≡ 5.24b, d, e, f, g, h, i - 5.24a exceeds cargo bay width.

b. Contamination may degrade astronomy module operation and Earth Survey (FPE 5.11) measurements unless sensor protective devices are provided.

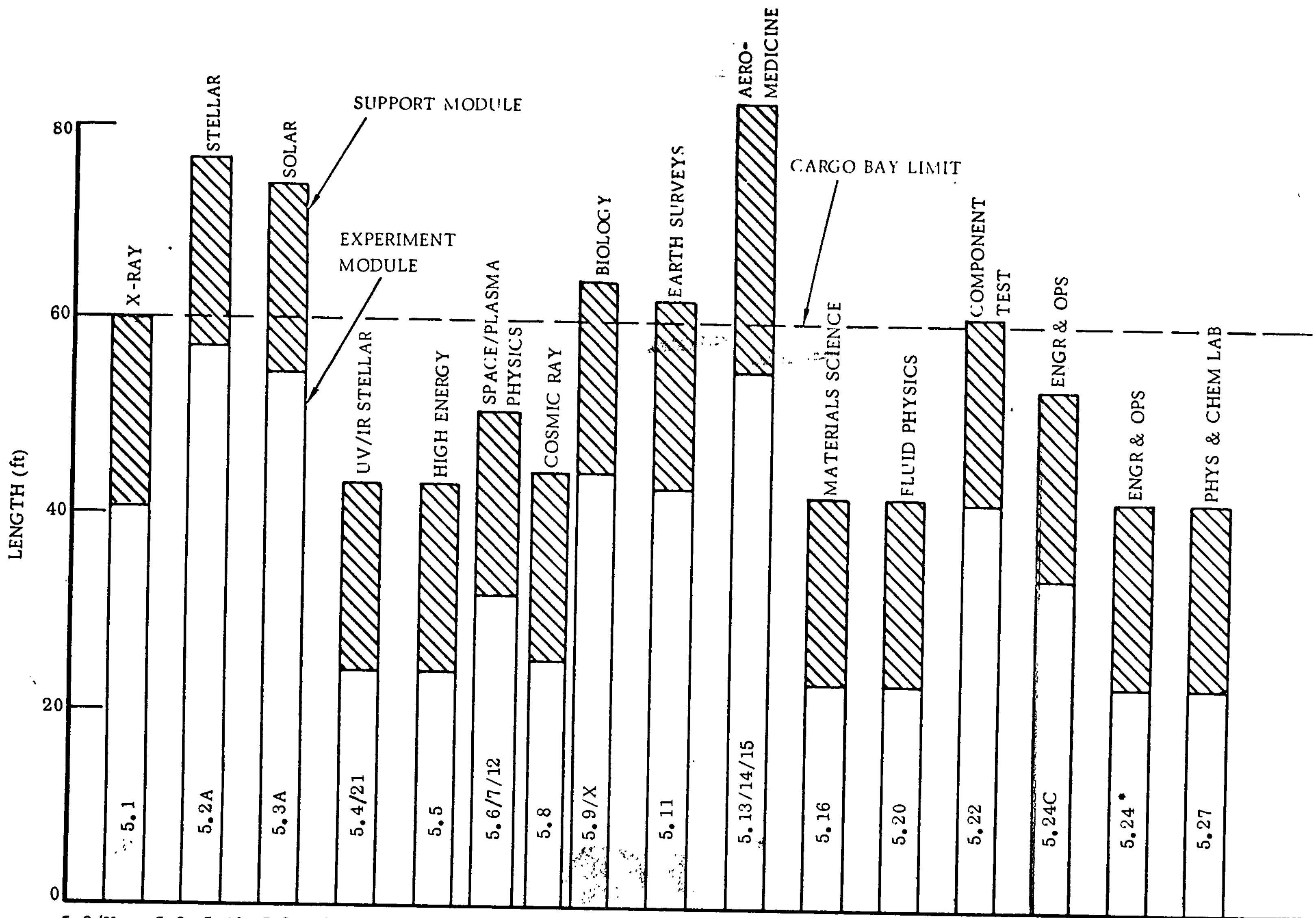
2.4.1 BOOST FEASIBILITY. Two parameters were used to assess the feasibility of boosting the experiment modules to orbit: length and weight. Shuttle launches are minimized by boosting both an experiment module and its support module and crew to orbit on the same flight. If the combined experiment/support module exceeds shuttle capabilities, the option still exists to boost the modules to orbit separately.

Length requirements for module combinations are shown in Figure 2-12. Ten of the 16 experiment and support module combinations will fit inside a 60-ft-long shuttle cargo bay. The diameter for FPE 5.24a exceeds the shuttle cargo bay limitations. The remaining seven experiment modules will individually fit inside the shuttle cargo bay, but a support module cannot be boosted with them.

Weight requirements of module combinations are summarized in Figure 2-13. This chart shows that none of the experiment modules can be boosted with a support module to a 270 n.mi. orbit at 55 deg inclination. However, all of the experiment and support modules can be boosted separately to the 270 n.mi. orbit (i.e., the experiment module weight is less than 35,000 lb) with the exception of the FPE 5.8 (Cosmic Ray) experiment module. The FPE 5.8 module can be boosted to a 155 n.mi. interim orbit at a 28.5 deg inclination, and from there the experiment module propulsion can be used to transfer the module to a 230 n.mi. orbit. Final circular orbit altitudes and whether the support and experiment modules are launched in combination or separately are tabulated in Table 2-9 for all FPEs.

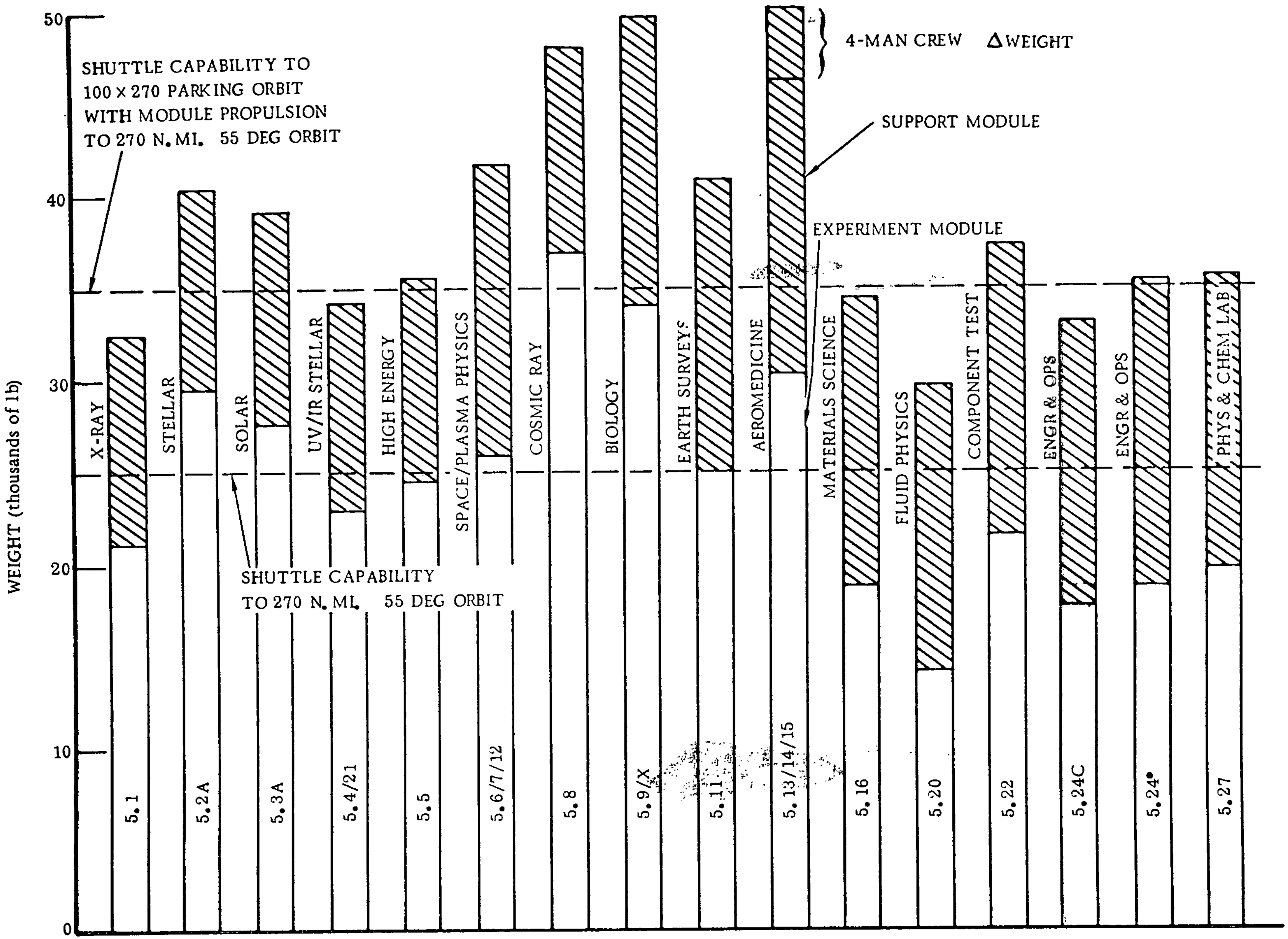
2.4.2 FEASIBILITY OF MEETING EXPERIMENT REQUIREMENTS. The feasibility of meeting experiment requirements for acceleration, stability, viewing, contamination and radiation with the shuttle-only concept are reviewed in the following paragraphs.

a. Acceleration. Experiments accomplished while the modules are detached from the shuttle will experience the same acceleration levels that were acceptable for the baseline space station based program. Those experiments accomplished while attached to the shuttle orbiter will experience a steady-state deceleration due to aerodynamic drag acting on the orbiter/experiment module/support module configuration. Aerodynamic drag deceleration is shown in Figure 2-14 for a vehicle with a ballistic coefficient (β) of 16.1 lb/ft^2. This is about the expected β for the orbiter when air flow is normal to the wing surfaces. Experiment altitude capabilities for all shuttle-only experiments are in excess of 200 n.mi. Drag deceleration for worst case atmosphere conditions (CIRA 65 Model 10 density data) will therefore be less than 10^{-6} g in all cases. This value is acceptable for all experiments.



5.9/X = 5.9, 5.10, 5.23, 5.25 and 5.26
* 5.24 b, d, e, f, g, h, i

Figure 2-12. Length Requirements of Module Combinations



5.9/X = 5.9, 5.10, 5.23, 5.25, and 5.26
• 5.24 b, d, e, f, g, h, j

Figure 2-13. Weight Requirements of Module Combinations

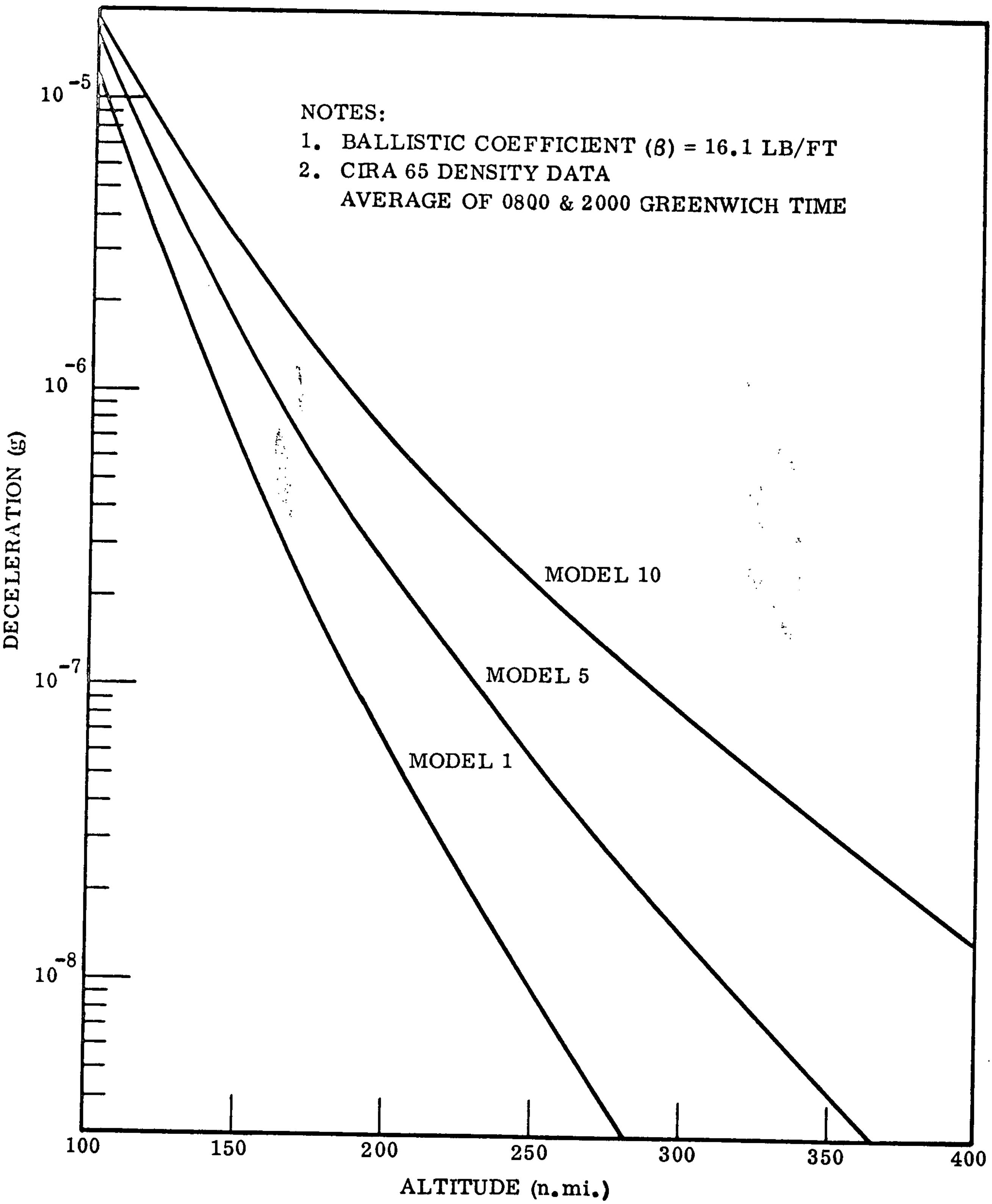


Figure 2-14. Aerodynamic Drag Deceleration

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Noise vibration and cyclic accelerations may, however, exceed the acceleration limits for the most acceleration sensitive experiments — FPE 5.10 (Plant Specimens - Bio E), FPE 5.16 (Materials Science), FPE 5.20-1 (Fluid Physics), FPE 5.25 (Microbiology), and FPE 5.27 (Physics and Chemistry laboratory). Special isolation mechanisms may be necessary to accomplish these experiments in the attached mode.

b. Stability. Four FPEs which are operational while attached to the orbiter have pointing and stability requirements which exceed the orbiters capability of 0.5 deg and 0.3 deg/sec respectively. FPE 5.6 (Space Physics) and 5.17 (Contamination) involve small instruments where the stability and pointing accuracy can best be provided by experiment-peculiar, gyro-stabilized platforms. FPE 5.11 and 5.22 require use of the experiment module RCS thrusters to reduce rates to acceptable levels. FPE 5.22 also requires additional experiment peculiar stability control.

c. Viewing. With the information presently available, it appears that viewing requirements can be met within the shuttle-only ground rules.

d. Contamination. The atmosphere surrounding the shuttle orbiter will contain effluents which could potentially interfere with astronomy, earth sensors, and other sensors. This interference could be temporary as in the case of condensation on lenses, of long duration as in the case of ice crystals forming from continuous atmosphere leakage, or from deposition on sensors. The potential for permanent damage to critical surfaces may also exist through chemical action of condensates or erosion by engine exhausts.

Contamination effects cannot be accurately predicted at this time. Experiment operational modes have therefore been selected to minimize potential degradation by contamination. Astronomy modules operate in the detached mode; when they are docked at the shuttle, contamination sensitive sensors are protected. Orbiter RCS thrusters are not used when earth surveys measurements are being taken — stability is maintained by the experiment module RCS thrusters which are directed away from the sensors. A protective cover is also available to shield the sensors during periods when experiments are not in progress.

e. Radiation. Radiation does not appear to be a driving requirements. Natural radiation levels in the shuttle-only program will be the equivalent of those for the space station based program. Induced radiation should be negligible since nuclear sources of electrical energy are planned only for FPE 5.24c (Brayton Isotope Power System).

2.4.3 FOUR-MAN SUPPORT MODULE EFFECTS ON EXPERIMENTS AND PROGRAM. The baseline support module provides support for two crewmen. At least a 4-man crew is needed to conduct some of the FPE 5.13 biomedical and behavioral experiments which require both subjects and two or three IMBLMS operators. Other affected experiments and FPE 5.24d, Advanced Orbital EVA, which requires two tethered EVA astronauts at one time. One or two "buddy" crewmen would be required to accomplish this experiment.

Other experiments in which a four-man support module capability are desirable are shown in Table 2-10. On-orbit service flight time for astronomy modules could also be reduced particularly if EVA operations were planned.

Table 2-10. Program Benefits With a 4-Man Support Module

FPE Affected	Title	Benefits
5.9 5.10 5.23 5.25 5.26	Space Biology	With suitable training could complete typical experiment program in one year with all five FPEs conducted concurrently. Approx. flight reduction = 10-12 30-day flights/year.
5.16	Materials Science & Proc.	Approx. flight reduction = 2-3 30-day flights/year.
5.27	Physics & Chem.	Approx. flight reduction = 1-2 30-day flights/year.

2.4.4 EXPERIMENT PROGRAM EFFECTS. The majority of experiments contained in the NASA Candidate Experiment program (Blue Book) can be accomplished using shuttle-only support to the experiment modules.

Some of the experiments affected by this mode of operation are summarized in Table 2-11. The more significant effects are:

FPE 5.3A Solar Astronomy. The requirement for real-time control of telescope pointing and sensor operation, normally satisfied by an observer in the space station (or by station to DRSS link to a ground observer) is provided in the shuttle-only mode only during the time the module is in contact with a MSFN station. (Significant only on the sunlit side of the orbit.) This amounts to about 20% of the normal real-time observation capability.

FPE 5.8 Cosmic Ray Lab. This laboratory contains some experiments that require the use of nuclear emulsions that have a normal life of three days due to their sensitivity to normal background radiation. In the normal station-supported mode, this lab is attached to the station where access for changing emulsions every three days is provided. In the shuttle-only mode of operation, these experiments can only be performed during the five-day stay time of the orbiter where a set is installed, exposed for three days, removed, and returned to the ground.

Table 2-11. Experiments Affected by Shuttle-Only Support

FPE	Title	Effect of Shuttle-Only Operation
5.3A	Solar	Real-time observer control limited to time during MSFN contact
5.8	Cosmic Ray	Experiments using nuclear emulsions conducted only during servicing periods
5.9/X	Biology	None — Assuming 2-day automation provided
5.13/14/15	Aeromedicine	Maximum 30-day stay time
5.17	Contamination	Space station peculiar contaminants not available
5.24	Engineering & Operations	5.24a Hangar — Limited to RMS/Module dimensions 5.24c Isotope - Reduced to one 7.5 kW system (diameter) 5.24d Advanced Orbital EVA — manned free-flying operation excluded

FPE 5.13/14/15 Aerospace Medicine. Experiments directed at determining the effects on man of long duration exposure to the space environment, are limited to 30 days maximum orbiter stay time by study ground rules. Also some of these experiments require four men, hence the four-man version crew module.

Other less significant effects of this mode are:

FPE 5.9/10/23/25/26 Biology. It is assumed that these experiments cannot be left unattended by man for periods exceeding 48 hours. Therefore, back-to-back shuttle flights are required, with experiments being capable of automated and/or remote operation during these unmanned, up to 48 hour periods. It should also be recognized that initiation of the lab in this operating mode places a serious committment on shuttle availability and stay time capability since extended periods without man's attendance could jeopardize the valuable specimens and experiments.

FPE 5.17 Contamination. Experiments would be limited to measurements of contaminating substances from the orbiter and modules which will not be representative of space station contaminants.

FPE 5.24 Engineering and Operations:

a. The 25-foot-diameter hangar cannot be provided in this mode, limiting experiments to what can be accomplished with remote maneuvering subsatellites.

b. Diameter limitations of the shuttle will permit only half of the 22-foot-diameter ring containing the two 7.5 kW isotope power supplies.

c. Advanced orbital EVA is considered as excluded by study ground rules since this would involve free flight of man from the shuttle/module complex.

The balance of the experiment program based on this preliminary analysis is not affected to any significant degree by this operational mode.

SECTION 3

DESIGN AND SUBSYSTEMS

3.1 CONFIGURATIONS

The four operational modes considered for the experiment modules operating on a shuttle-only mission comprise different combinations of attached and detached operation. In general, the detached operations include the astronomy FPEs while the attached operations include the laboratory type modules such as Biology, Materials Science, Component Test, and Earth Surveys. In both cases the experiment operation is supported by a module that remains attached to the shuttle orbiter vehicle. The support module is used to support the experiment operations and scientist-astronauts while in orbit.

The free-flying experiment modules are maintained and serviced by the support module (Figure 3-1). This module is swung out from the cargo bay to permit docking of the free-flying module. At the time of docking the experiment module, solar array panels and magnetic booms are retracted to minimize docking loads on those members and to provide maximum maneuvering clearance. After docking, the experiment module relies on the support module subsystems.

The experiment modules that are normally operated in an attached mode with the space station complex also remain attached to the support module for shuttle-only operation (Figure 3-2). In this operating mode, the experiment is operated for a period of 5 to 30 days depending on the experiment duration requirements. The support module, designed to serve as an interim space station facility, furnishes support requirements such as electrical power, life support, and thermal control to the attached operating experiment module. The attitude control system of the experiment module may be used in certain cases to provide experiment orientation and stability requirements.

3.1.1 <u>EXPERIMENT MODULE CONFIGURATIONS AND MODIFICATIONS FOR SHUTTLE-ONLY OPERATION.</u> The astronomy free-flying modules have been modified by the addition of a data kit which is used for storage of astronomical data until such time that it can be relayed to earth. This modification is peculiar to the CM-1 common module. (Figure 3-3.)

The CM-3 module has been modified for dormancy operation (i.e., for time untended in-orbit) by the addition of a 660-square-foot solar array from the CM-1 module and an electrical power control panel. Continued experiment duration beyond the maximum 30-day capability of the support module/shuttle orbiter is thus provided for such FPEs as the small vertebrates and plant growth experiments (Figure 3-4).

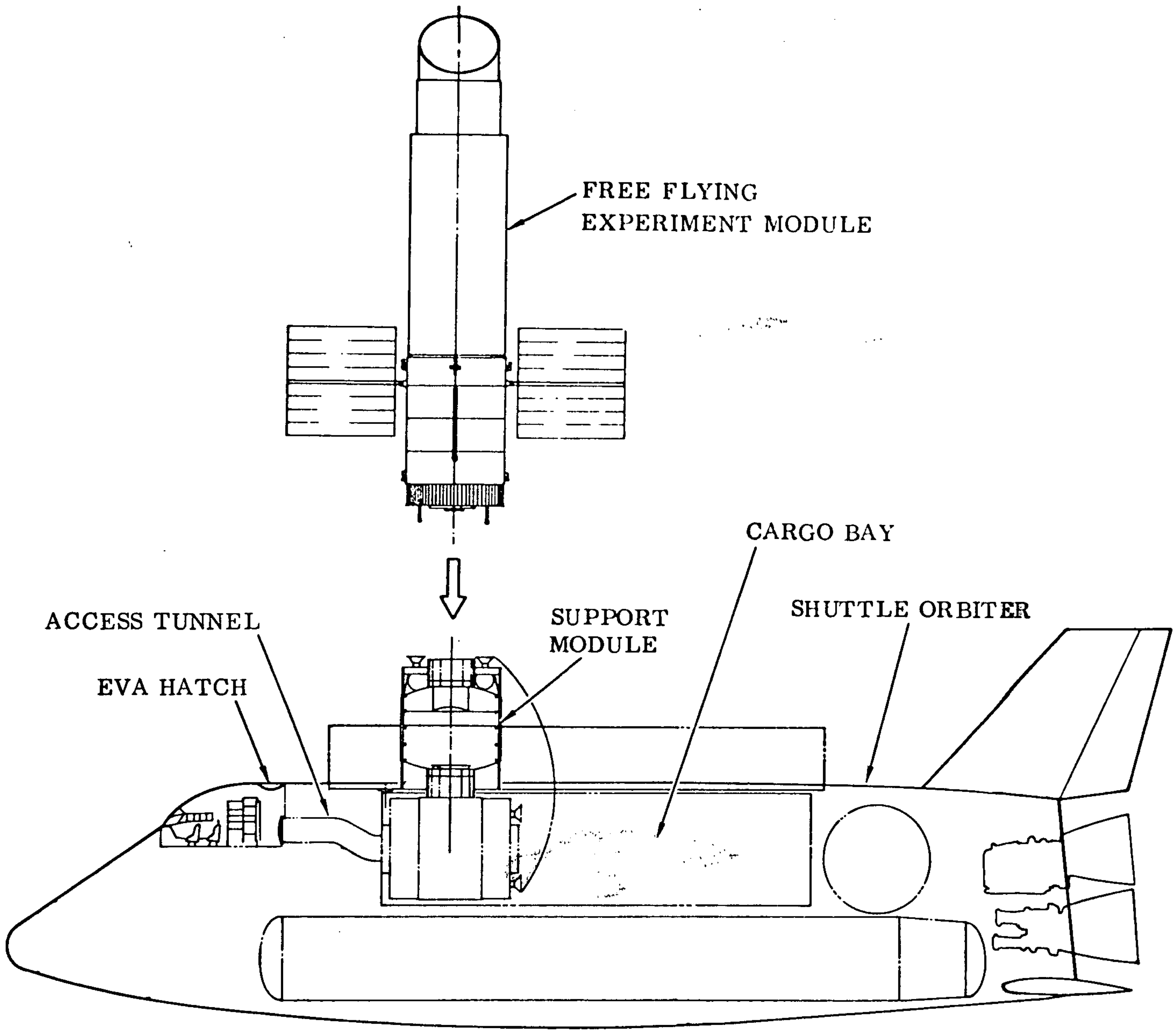

Figure 3-1. Detached Module, Shuttle Only

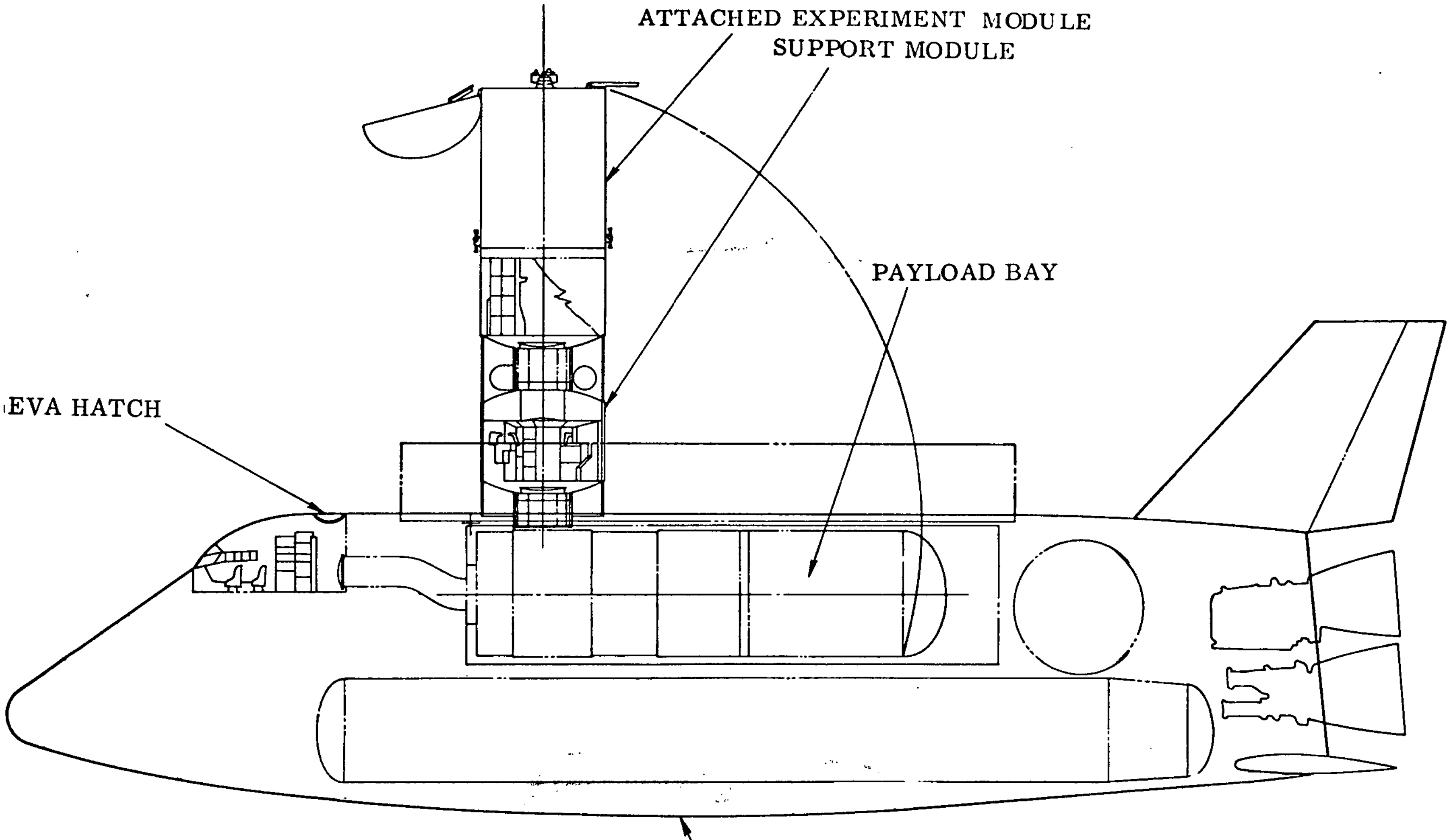

Figure 3-2. Attached Module, Shuttle Only

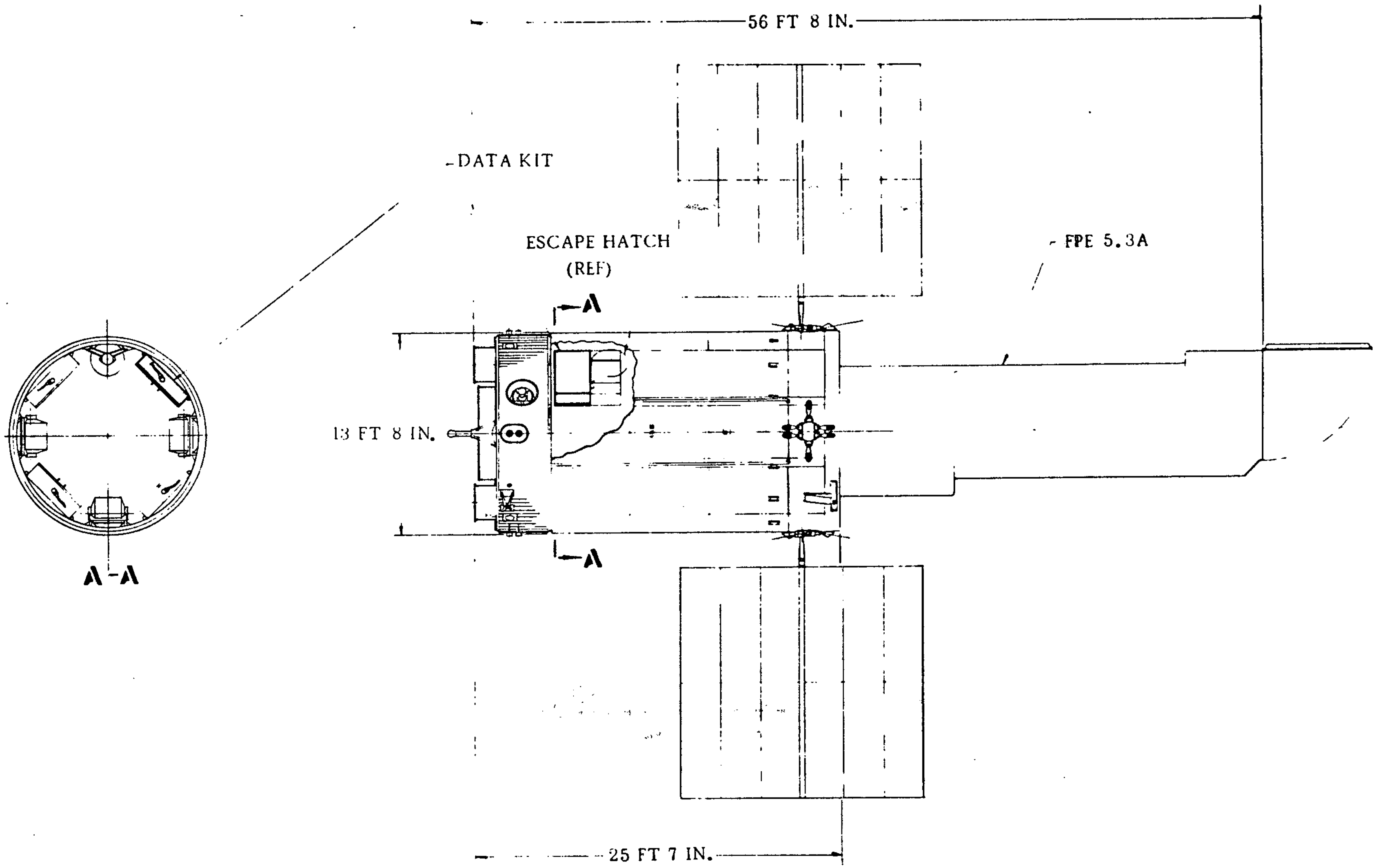

Figure 3-3. CM-1 - Shuttle-Only Configuration

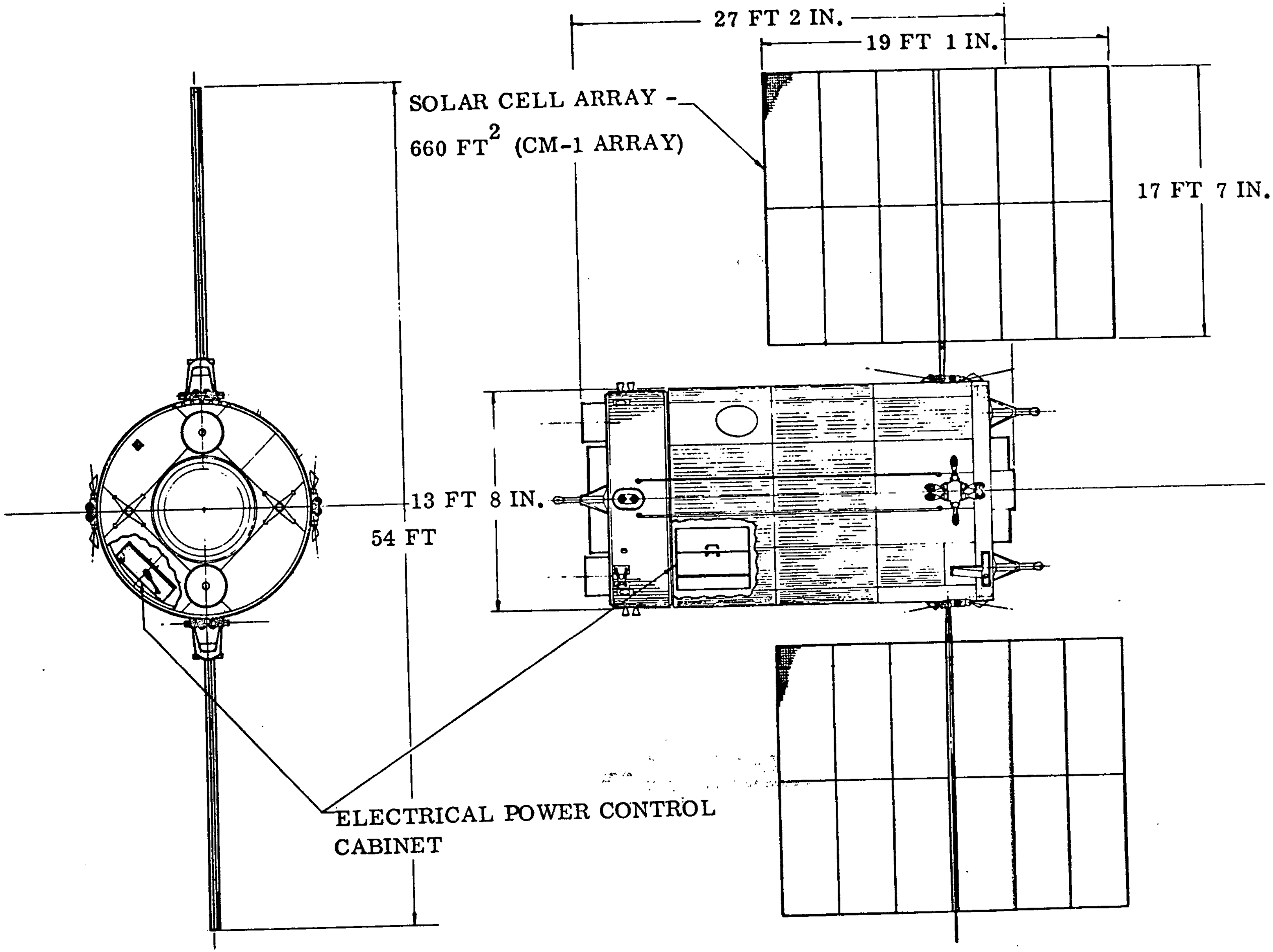

Figure 3-4. CM-3 - Shuttle-Only Configuration

FPEs 5.4 and 5.21 (added for this task) have been accommodated in an additional CM-1 module. In this configuration the 0.3 meter Schmidt normal incidence telescope and the 1.0 meter infrared normal incidence telescope are mounted to the instrument-peculiar forward bulkhead. The instruments are housed entirely within the module utilizing viewing ports in the bulkhead. The Schmidt instrument is gimbal mounted to provide rotation along its viewing axis while the 1.0 meter instrument relies on spacecraft rotation. In this way desired angular rotation between the two instruments may be achieved. The configuration is shown in Figure 3-5.

3.1.2 SUPPORT MODULE CONFIGURATIONS. The support module shown in Figure 3-6 is a single-compartment module designed to support two scientist-astronauts for 5 to 30 days in orbit while attached to the shuttle orbiter. The module has been designed to operate with either the attached or detached experiment modules. Most of the support module structure is identical to that used for the experiment modules.

3.1.2.1 Configuration for Attached Module Operation. The attached experiment module is permanently attached to the support module using a fixed adapter section. For this configuration the 36-in. long tunnel section and 48-in. skirt, with the integral docking structure, is removed from the support module. The 48-in. skirt and docking structure is also removed from the experiment module. This provides an 8-ft airlock between the support module and experiment module.

The pressurized compartment has a wall length of 9 ft; 7 ft is used for the habitable area and 2 ft is used for the pressurized subsystems area. Access to the subsystems area is through the movable floor panels. With all the equipment mounted to the module wall, the floor sections may be swung aside in the plane of the floor to expose the various subsystem components. Twelve such floor sections are provided.

The exterior surface of the pressurized compartment is covered with radiator panels for the thermal control system; up to 400 sq ft is available. The thermal control panels also serve as meteoroid protection for the habitable area of the module.

Tankage for up to 2500 lb of fuel cell reactants, LO_2 and LH_2, are provided in the skirt area of the module outside the habitable area. This tankage is divided into two cylindrical LH_2 tanks and four spheres for the LO_2. The fuel cell modules themselves are located under the floor panels, together with the thermal control unit and product water system. The control subsystem is incorporated into a console in the habitable area.

The habitable floor area is divided into three functional areas: experiment peculiar instrumentation, module subsystems, and life support.

3.1.2.2 Configuration for Detached Module Operation. The basic structural and subsystems configurations are in most cases the same as those described for the attached operating version. Refueling propellant storage tanks are, however, provided.

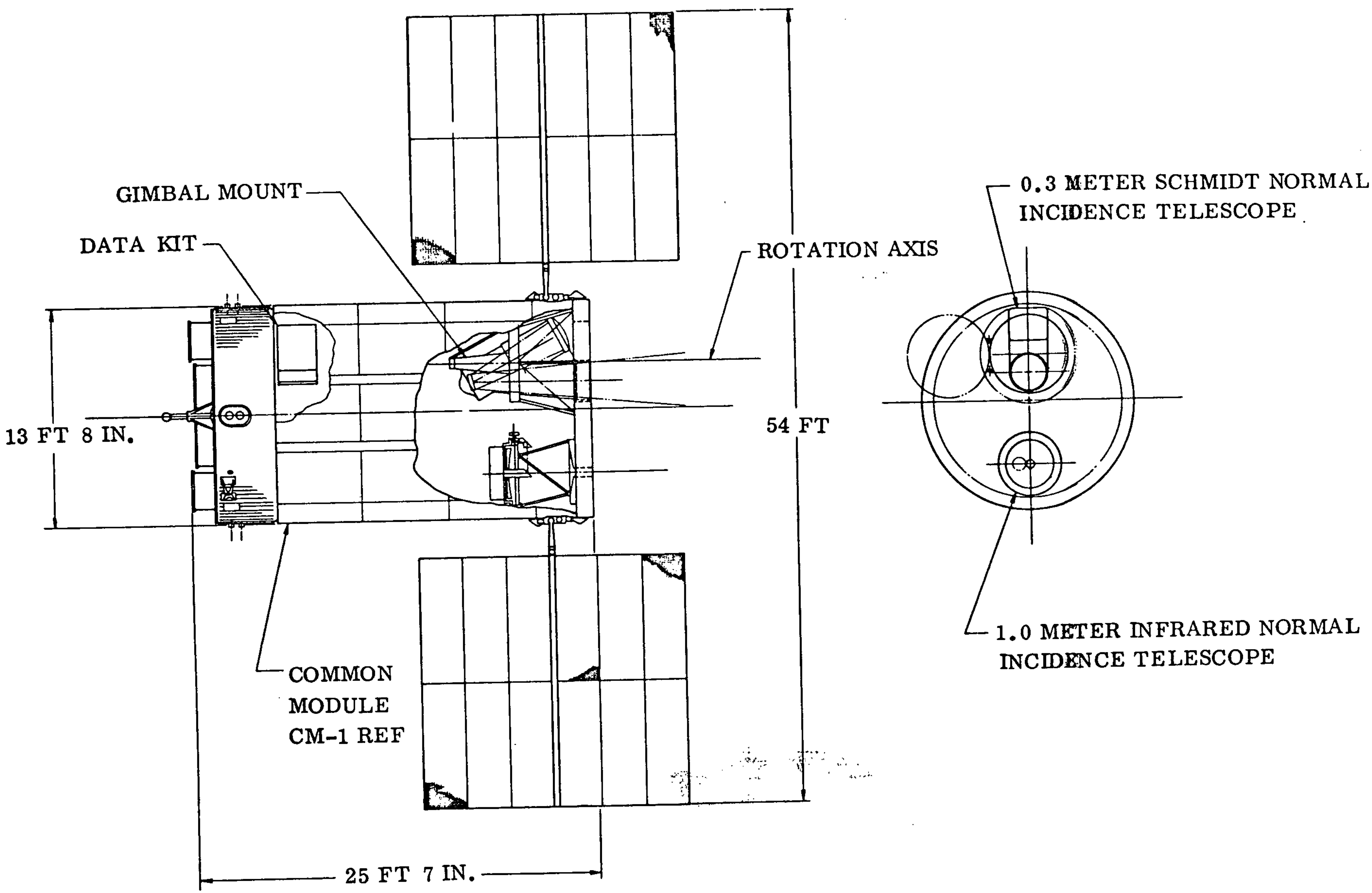

Figure 3-5. Stellar Survey FPEs in CM-1 Module

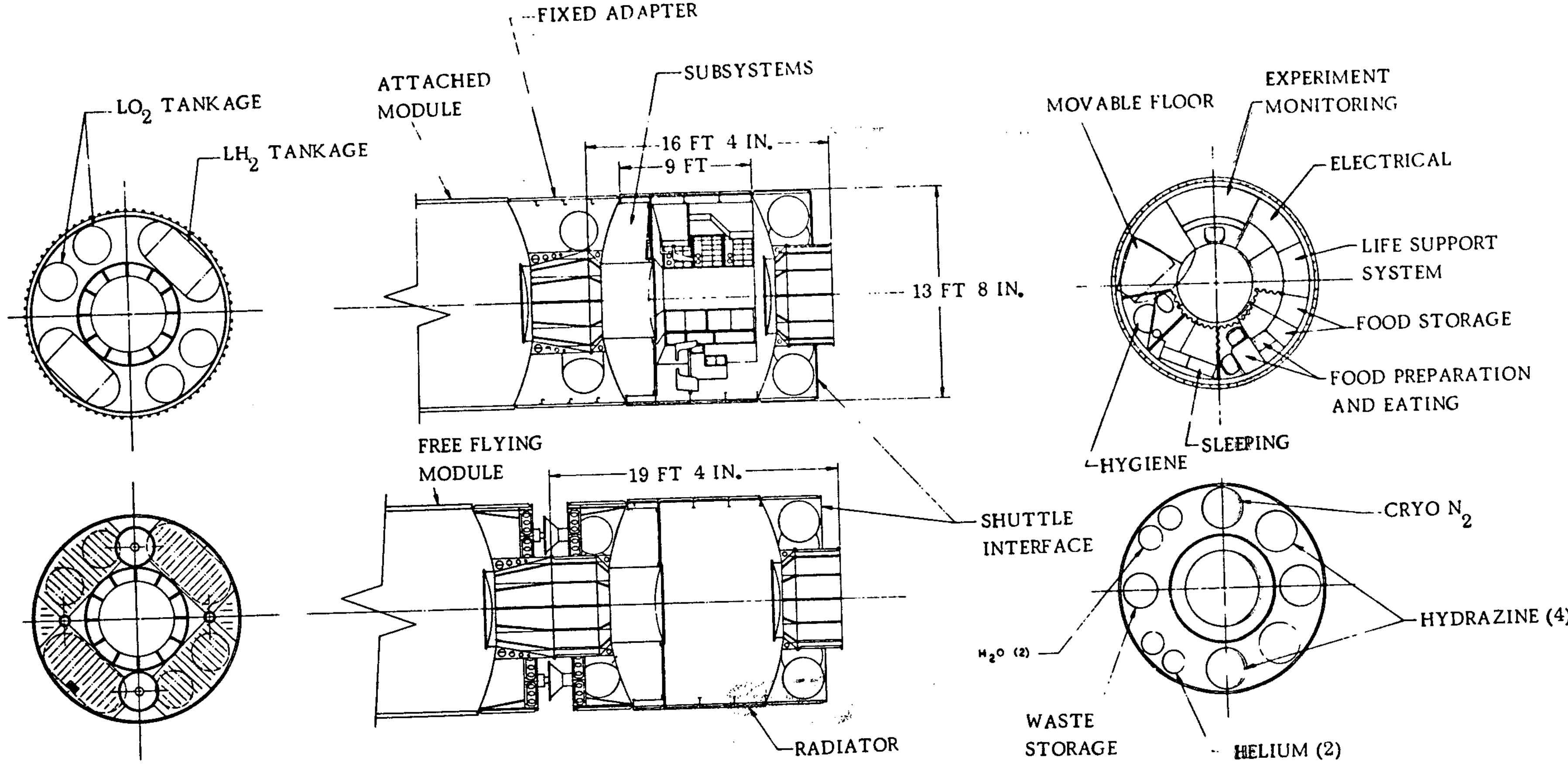

Figure 3-6. Support Module-Shuttle-Only Operation

The module structure is modified by deleting the fixed adapter structure and adding the 36-in.-long tunnel section together with the 48-in. skirt section and docking structure.

The support module overall length for the detached experiment module version is 19 ft 4 in.; this is 3 ft longer than the attached version because a 3-ft tunnel section is added to provide the proper docking geometry for the experiment module.

3.1.2.3 Alternate Four-Man Support Module Configurations. The basic configuration for an alternate four-man support module is a two-deck module with one deck used for general living quarters for 5 to 30 days (Figure 3-7). The second deck is used to house the experiment unique test and monitoring equipment. The deck used for living quarters is not modified from mission to mission but the experiment monitoring equipment is changed to suit the requirements of this experiment.

Other than the two decks the general configuration of the 4-man support module is identical to the 2-man module with modifications to the subsystems required for the two additional crew members.

3.2 MASS PROPERTIES

Mass properties data have been developed for all experiment module/FPE configurations considered in the shuttle-only task. These data are summarized in Table 3-1.

Weight summaries for support modules for 2-man/5- and 30-day and 4-man/30-day missions are provided in Table 3-2.

The basis for weight estimates is:

Experiment:	NASA "Blue Book" including update material and shuttle-only adjustments as indicated in Section 2.2.
Structure:	Same as baseline. Compatible with expendable and shuttle launch.
Propulsion and R.C.S.:	Same as baseline. Identical system and capacities on all modules. Dry tankage and propellant off-loading specified where applicable.
Electrical Power:	CM-1 modules are same as baseline (solar arrays providing primary power). CM-3 and CM-4 modules incorporate similar arrays where required and support module provides electrical power using fuel cell systems.
Guidance and Navigation:	Same as baseline (docking targets, corner reflectors, etc).
Stabilization Control:	Same as baseline. Modularized tri-axial bar magnets and other components as identified in Section 3.3.

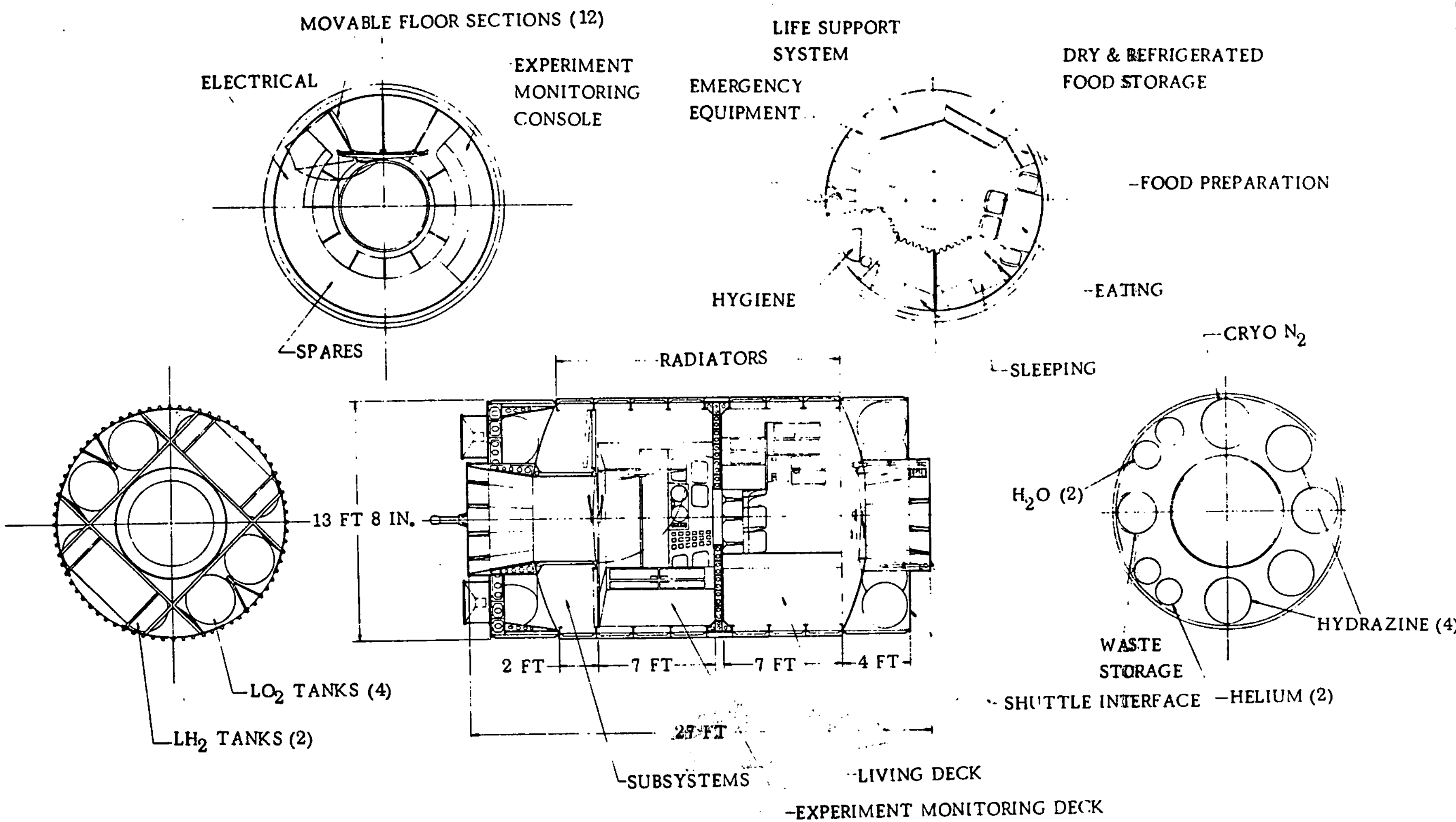

Figure 3-7. 4-Man Support Module

Table 3-1. Weight Summary - Experiment Module Study/Shuttle-Only Configurations

Item	FPE	Title	S/O Concept	CM-	Exp Equip Wt-Baseline	XMod Wt Baseline	Δ Wt Exper	Δ Wt Subsyst	Σ Wt XMod Expend'bls	Shuttle Only XMod Wt On-Orbit	Crew Support Module Type	Crew Support Module Weight (lb)
1	5.1	X-ray Astronomy	A	1	3,300	21,075	—	+120	2,590 (1)	21,195 (1)	2 man - 5 day	11,795
2	5.2A	Stellar Astronomy	A	1	8,300	29,509	—	+120	2,590 (1)	29,629 (1)	2 man - 5 day	11,795
3	5.3	Solar Astronomy	A	1	6,420	27,672	—	+120	2,590 (1)	27,792 (1)	2 man - 5 day	11,795
4	5.4 5.21	U.V. Stellar Survey I.R. Stellar Survey	A	1	3,500	—	—	—	2,590 (1)	22,945 (1)	2 man - 5 day	11,795
5	5.5	High Energy Stellar	A	1	7,800	24,424	—	+120	2,590 (1)	24,544 (1)	2 man - 5 day	11,795
6	5.6 5.7 5.12	Space Physics Plasma Physics Remote Maneuvering	C	4	3,900	21,648	3,625 (5.6 & 7)	+717	2,590 (1)	25,990 (1)	2 man - 5 day	11,795
7	5.8	Cosmic Ray Physics	A	1	19,500	—	—	—	2,590 (1)	36,954 (1)	2 man - 5 day	11,795
8	5.9 5.10 5.23 5.25 5.26	Biology - Small Vertebrae Biology - Plant Specimens Biology - Primates Biology - Micro Biology Biology - Invertebrates	C	3	8,457	27,802	+3,820	+2440	3,590 (2)	34,062 (2)	2 man - 30 day 4 man - 30 day	16,300 (20,475)
9	5.11	Earth Surveys	C	4	4,550	24,448	—	+695	2,590 (1)	25,143 (1)	2 man - 30 day	16,300
10	5.13 5.14 5.15	Biomedical & Behavioral Man/Systems Integration Life Support	C	4	7,068	29,463	—	+889	2,590 (1)	30,352 (1)	2 man - 30 day 4 man - 30 day	16,300 (20,475)
11	5.16	Material Sciences	B	3	7,750	20,551	-2,360	-160	2,590 (1)	18,671 (1)	2 man - 30 day	16,300
12	5.20-1	Fluid Physics - Laboratory	B	3	785	13,586	—	-160	2,590 (1)	14,066 (1)	2 man - 30 day	16,300
13	5.20-2	Fluid Physics - Non-Cryogens	A	1	5,000	26,926	—	+120	7,490 (4)	27,686 (3)		
14	5.20-3	Fluid Physics - Int Term Cryogens	A	1	3,010	—	—	—	—	28,012 (4)		
15	5.20-4	Fluid Physics - Long Term Cryogens	A	1	5,250	—	—	—	—	30,252 (4)		
16	5.22	Component Test	C	4	2,000	19,538	—	+1401	2,590 (1)	21,579 (1)	2 man - 30 day	16,300
17	5.24b	Exp a Guidance Stab & Control	C	(5)	—	—	37,000	—	—	37,000 (5)	2 man - 5 day	11,795

(Continued)

Table 3-1. Weight Summary - Experiment Module Study/Shuttle-Only Configurations, Contd

Item	FPE	Title	S/O Concept	CM-	Exp Equip Wt-Baseline	XMod Wt Baseline	Δ Wt Exper	Δ Wt Subsyst	Σ Wt XMod Expend'bls	Shuttle Only XMod Wt On-Orbit	Crew Support Module Type	Crew Support Module Weight (lb)
18	5.24b 5.24b 5.24d 5.24e 5.24f 5.24g 5.24h 5.24i	Exp b Guidance Stab & Control Exp c Guidance Stab & Control Engr & Oper Advanced EVA Engr & Oper Maint & Repair Engr & Oper Logistics & Resupply Engr & Oper Space Living Engr & Oper Wireless Power Engr & Oper Laser Communications	C	3	13,650	—	—	—	2,590 (1)	29,301 (1)	2 man - 30 day	16,300
19	5.24c	Engr & Oper Brayton Power Sys	C	4	15,100 (incl shroud)	—	—	—	2,590 (1)	32,575 (1)	2 man - 30 day	16,300
20	5.27	Physics & Chemistry	B	3	7,185	—	—	—	2,590 (1)	20,501 (1)	2 man - 30 day	16,300

NOTES:
(1) Includes RCS tankage fill-up of 2560 lb plus 30 lb ECS fluids.
(2) Same as Note (1) plus approx. 1000 lb of experiment (L.S.S.) consumables
(3) Includes 4900 lb of propulsion slice (CM-2) fuel
(4) Uses same CM-1 & propulsion slice as FPE 5.20-2 - includes 5.20-2 dry experiment wt = 2316 lb + 4900 lb of fuel
(5) No Xmod required. 37,000 lb experiment flies solo - combined with support module when attached

See Section 2.4, Table 2-10 for launch weight data

Table 3-2. Weight Summary - Crew Support Modules

Item/System	2-Man, 5-Day Configuration Weight (lb)	2-Man, 30-Day Configuration Weight (lb)	4-Man, 30-Day Configuration Weight (lb)
Cylinder - Shell	690	690	1,300
Domed Bulkheads	2,225	2,225	2,225
Aft Skirt, Flange, and External Structure	645	645	645
Fwd Skirt	465	465	465
Floors and Int Struct	100	100	600
Docking Struct & Equip or Integral Connection	735	735	735
Tunnel - Personnel Ingress/Egress (2)	300	300	300
Shuttle Interface Provisions	400	400	400
Subtotal - Structure	5,560	5,560	6,670
Life Support System (including expendables)	2,240	3,495	4,990
Electrical Power System (maximum)	2,210	5,460	6,500
Environmental Control System	1,000	1,000	1,500
Communications & Data Management System	170	170	200
Guidance & Navigation System	45	45	45
*RCS - XMod Fuel Resupply Tankage & Distribution System - Dry	570	570	570
TOTAL — Crew Support Module	11,795	16,300	20,475

*Capacity = 2560 lb fuel

Communications & Data Management:	Similar to baseline plus additional data storage and recorders where applicable.
Thermal Control System:	Same as baseline. See Section 3.8
Environmental Control and Life Support System:	Same as baseline. See Section 3.9

3.3 STABILIZATION AND CONTROL SUBSYSTEM

Table 3-3 summarizes the experiment orientation, pointing, and low-g requirements pertinent to the shuttle-only concept. Note that the astronomy FPEs are not listed because the requirement pertinent to shuttle-only concept is that of the servicing period only. As indicated, a ±5 deg attitude hold is judged adequate for this mode.

As used in Table 3-3 NR (not required) in regard to orientation means the experiment has no preference. NR applied to pointing or low-g means that there is no special requirement by the experiment.

Orbit stay time is an important parameter. For Concept A, servicing periods of 1 to 5 days are considered. For Concepts B, C, and D, operating periods up to 30 days apparently suffice. For the dormant period of Concept C, up to 60 days may be required. The orbit stay times given above are probably not final. However, the stability and control scheme is generally evaluated on the ability to produce the required control for approximately these stay times.

3.3.1 ALTERNATE ATTITUDE CONTROL CONCEPTS. Appropriate alternate attitude control concepts are:

a. Three Axis RCS. RCSs exist on the shuttle and experiment module or could be added to the support module. This technique is suitable for missions with moderate stability requirements and short time periods between propellant resupply and is considered for both shuttle-attached and dormant experiment module operating modes.

b. Dual Spin. Where one inert (or slowly rotating) spacecraft axis is permiss flywheel spinning about this axis provides stability about the transverse axes. Control about the spin axis and drift correction can be supplied by RCS or magnetic torquing. Moderate stability ($\sim$ 1 degree) is available with these methods. These similiar systems are considered for the dormant operating mode only. For the shuttle-attached mode, either flywheel size or required accuracy make the system unsuitable.

Table 3-3. Shuttle-Only Stability and Control Requirements by Experiment Group

Concept	Experiment Group	Orien- tation	Pointing Accuracy (± deg)	Pointing Stab. (deg/sec)	Low G (g's)
A	Astronomy (2)	NR	5	NR	NR
	Cosmic Ray (8)	Earth	±30°	NR	NR
	Cosmic Ray (2)	Earth	5	NR	NR
B	Matl. Sciences (5.16)	NR	NR	NR	$<10^{-5}$
	Fluid Physics (5.20-1)	NR	NR	NR	$<10^{-4}$
	Phys. & Chem. (5.27)	NR	NR	NR	$<10^{-4}$, 10^{-6}(3)
	Earth Surveys (5.11), (1)	Earth	0.5	0.03	NR
C	Plasma (5.7/5.12), (6) } (4), (7)	NR	0.5, 5.0	0.3	NR
	Airlock (5.6), (5) }	Earth	0.5, 5.0	0.03	NR
	Biology (5.9/5.26) }	NR	NR	NR	10^{-3}(90%), $<10^{-2}$
	Biology (5.10/5.25) } (4), (6)	NR	NR	NR	10^{-5} (95%), $<10^{-4}$
	Biology (5.23) }	NR	NR	NR	$<10^{-3}$
	Earth Surveys (5.11), (7)	Earth	0.5	0.03	NR
	Aeromed (5.13/14/15), (7)	NR	NR	NR	$<2 \times 10^{-3}$ g, $<0.03°/sec^2$
	Eng. Oper. (5.24), (5), (7)	Any	0.5, 5.0	0.3	NR
	Comp. Test (5.22), (6), (7), (5)	Earth	0.5, 5.0	0.02	NR
D	Plasma (5.7/5.12), (1) }	NR	0.5, 5.0	0.3	NR
	Airlock (5.6), (5) }				
	Earth Surveys (5.11), (1)	Earth	0.5	0.03	NR

(1) Alternate operating mode.

(2) Requirements during attached servicing mode only.

(3) One experiment requires 10^{-6} g, the others require 10^{-5} g maximum

(4) Different FPE's in same module.

(5) Requirements at module only. Experiment includes equipment to refine as required

(6) These requirements also apply for the dormant mode.

(7) The requirements apply only when attached to the shuttle. For the dormant period Low G requirements do not apply and ±5 deg attitude accuracy is considered sufficient.

(8) During detached operation.

NR = Not Required.

c. Three Axis Momentum Exchange Actuation. The combined IW/CMG momentum exchange actuation, magnetic dumping system currently used in the free-flying experiment module CM-1 for the astronomy mission provides sub-arc-sec stability for long term missions. This system is described in the interim report and is not discussed further here. Its use for the astronomy missions in CM-1 is retained for shuttle only.

d. Cosmic Ray Experiment (FPE 5.8). The cosmic ray experiment (housing the super conducting magnet) is housed aboard a CM-1 module for the shuttle-only case. The CM-1 SCS is retained but stripped of the reaction wheels, star tracker components plus their support electronics. The remaining CMG system is used to control the vehicle.

e. Gravity Gradient. Where an earth-bound orientation with the spacecraft long axis aligned with local vertical is permitted, gravity gradient (GG) can be used. This system is considered for the dormant operating mode only. The required vibration damper size is prohibitive for the shuttle-attached mode.

3.3.2 SHUTTLE ATTACHED RCS ATTITUDE CONTROL. For the shuttle-attached mode, either the experiment module or shuttle RCS could be used to control the combination in attitude. The principal factor in selection is fuel consumption for (1) the inherent RCS limit cycle and (2) reacting the environment. These are evaluated below.

3.3.2.1 Limit Cycle Fuel Consumption. A simultaneous three-axis limit cycle situation is used to size fuel consumption. The fuel rate is,

$$\text{Fuel (lb/sec)} = (3/2)\,(F\,\Delta t)^2\;R/(JI_{sp}\Delta\theta) \tag{1}$$

$$\text{(lb/day)} = 1.3 \times 10^5\;(F\,\Delta t)^2\;R/(JI_{sp}\Delta\theta)$$

where F is the thrust level in lb

Δt is the equivalent time of the minimum impulse bit in sec

R is the thruster pair delivering the control moment separation distance in feet

J is the vehicle inertia in slug-ft^2

I_{sp} is the fuel specific impulse (minimum impulse value) in sec

$\Delta\theta$ is the required angular accuracy in radians ($\pm$)

Table 3-4 lists the numerical values used for the shuttle and experiment module systems.

Table 3-4. RCS Limit Cycle Parameters

	Shuttle	Experiment Module
Thruster force, F, lb	1,500	140
Thruster separation, R, ft		
Pitch/yaw	60	15
Roll	20	15
Propellants	Hydrogen/Oxygen	Hydrazine
Minimum impulse, $\Delta t/I_{sp}$ sec†	0.035/408	0.01/150
Inertia, J, slug-ft^2		
Pitch/yaw	15×10^6	
Roll	3.4×10^6	

† Estimated minimum impulse values from Convair in-house experiment module and shuttle studies.

The ratio of R/J used was that for pitch/yaw. The small difference in roll for the shuttle is ignored. For the experiment module, it is assumed that the roll thrusters force level is adjusted to yield the same fuel consumption as in pitch/yaw. The parameter values were obtained from the current Convair experiment module and shuttle contract work. The values, particularly those for the shuttle engines, are regarded as preliminary estimates only.

The resultant fuel consumption to maintain the limit cycle is plotted as a function of the required accuracy on Figure 3-8. As indicated, the advantageous factor of shuttle fuel specific impulse is offset by the higher values of thruster force level and minimum impulse bit. The fuel rate from the shuttle RCS is 20 times that resulting from use of the experiment module thrusters. For reference, the required accuracy levels of 0.5 and 5 degrees are moted. It would appear that the experiment module thrusters should be used to satisfy the more demanding attitude accuracy experiments. Alternatively, an order of magnitude lower level on the shuttle RCS thrusters would be beneficial.

The minimum angular rate resulting from a minimum impulse is also of interest. In addition, the angular acceleration during thruster firing induces a linear acceleration at points off the rotational axis of the shuttle. These values are given in Table 3-5.

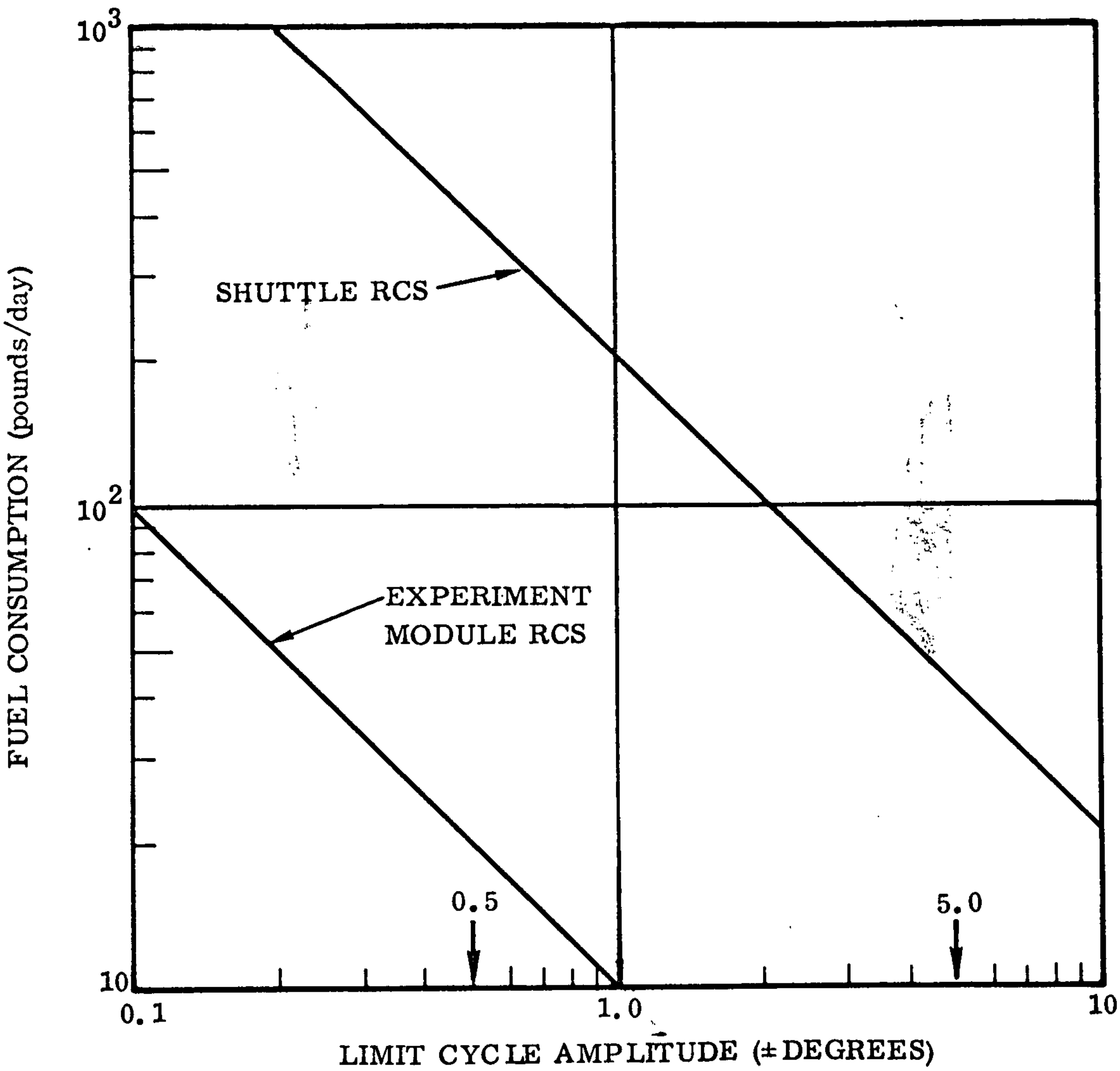

Figure 3-8. Estimated RCS Limit Cycle Fuel Consumption Depending on Use of Shuttle or Experiment Module Thrusters, Shuttle Attached Configurations

Table 3-5. Angular Rate, Linear Acceleration Induced by Thruster Firing

RCS Source	Experiment Module	Shuttle
Angular velocity (deg/sec)††	0.4×10^{-4}	0.006
Angular acceleration (deg/sec^2)††	0.8×10^{-2}	0.344
Linear acceleration (g)†	1.4×10^{-4}	6×10^{-3}

† At 32.2 ft from the shuttle/crew module/experiment module combined cg.
†† Pitch/yaw values.

While the minimum impulses from the experiment module RCS are considerably lower than the shuttle, use of the shuttle RCS at the present thruster level is still acceptable for many experiments, but again lower thrust values would be preferred. The linear acceleration level noted is about an order of magnitude higher than that predicted for a space station hardmount.

3.3.2.2 Reacting the Environment. Gravitational torque is the major source of environment perturbation. The fuel expenditure required is independent of accuracy but dependent on spacecraft orientation. In this regard both earth and inert shuttle orientations are of interest. For an earth-oriented shuttle,

$$\text{Fuel (lb/sec)} = (3/2)NW_o^2 J \sin 2\theta_e/(RI_{sp}) \tag{2}$$

$$\text{(lb/day)} = 0.22 J \sin 2\theta_e/(RI_{sp})$$

where W_o is the orbit rate (1.1×10^{-3} rad/sec)

θ_e is the angle between one of the shuttle principal axes and the earth local vertical

N is a geometrical efficiency factor (vectoring of thrust from two nozzles to off-set the gravitational torque impulse, $N = \sqrt{2}$)

For a pusedo-inertial* oriented shuttle,

$$\text{Fuel (lb/day)} = 8.27 \times 10^4 W_o^2 J \cos\theta_o (1 + \pi/2 \sin\theta_o)/RI_{sp}) \tag{3}$$

where θ_o is the angle between the shuttle minimum moment of inertia axis and the orbit plane

*If the orbit plane were stationary in space the shuttle orientation would be truly inertial. the term pusedo-inertial used here means nearly inertial (5 deg/day due to orbit and solar rate).

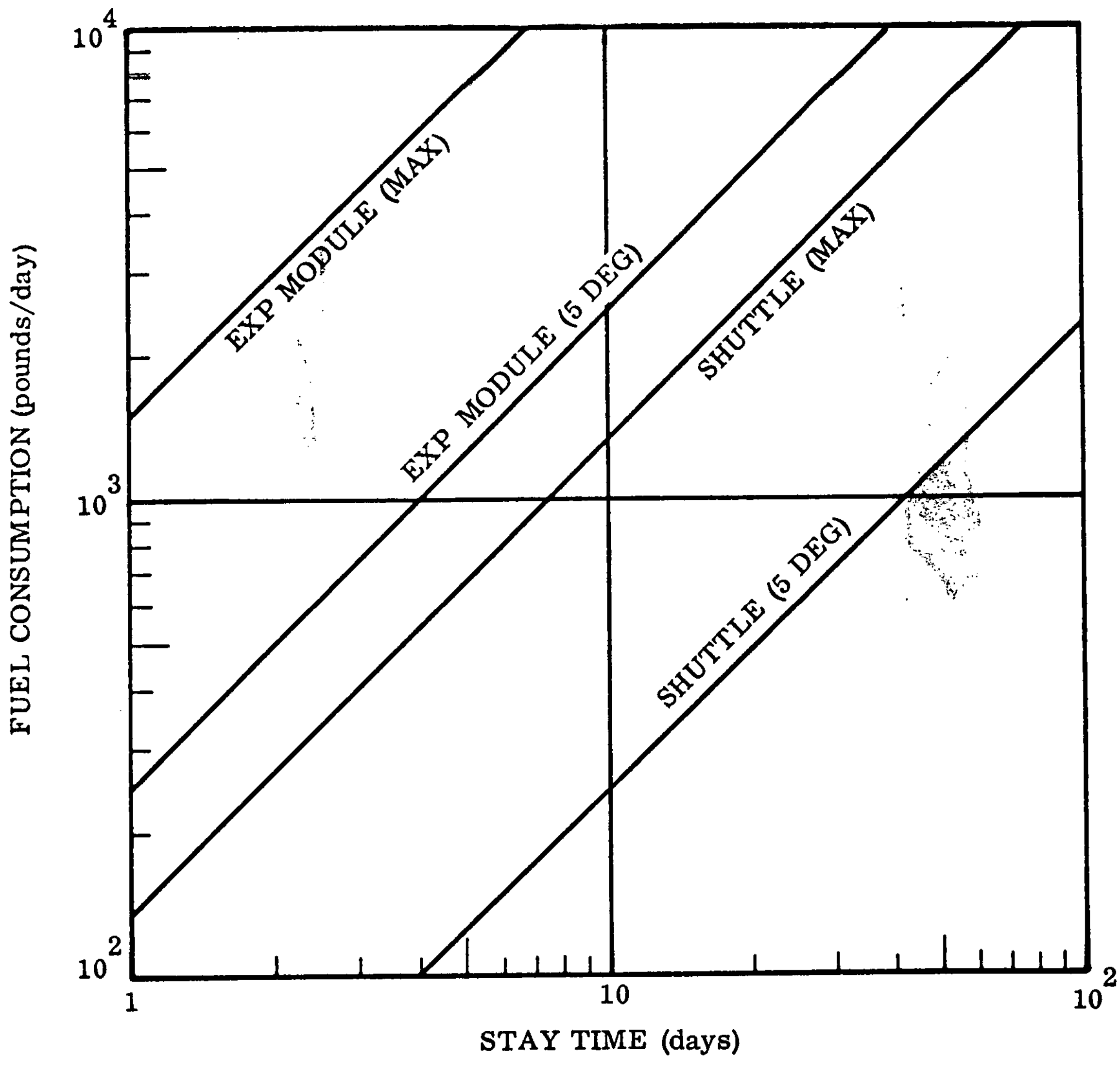

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Figure 3-9. Estimated Fuel Requirement for Earth Orientations Using Either Shuttle or Experiment Module RCS

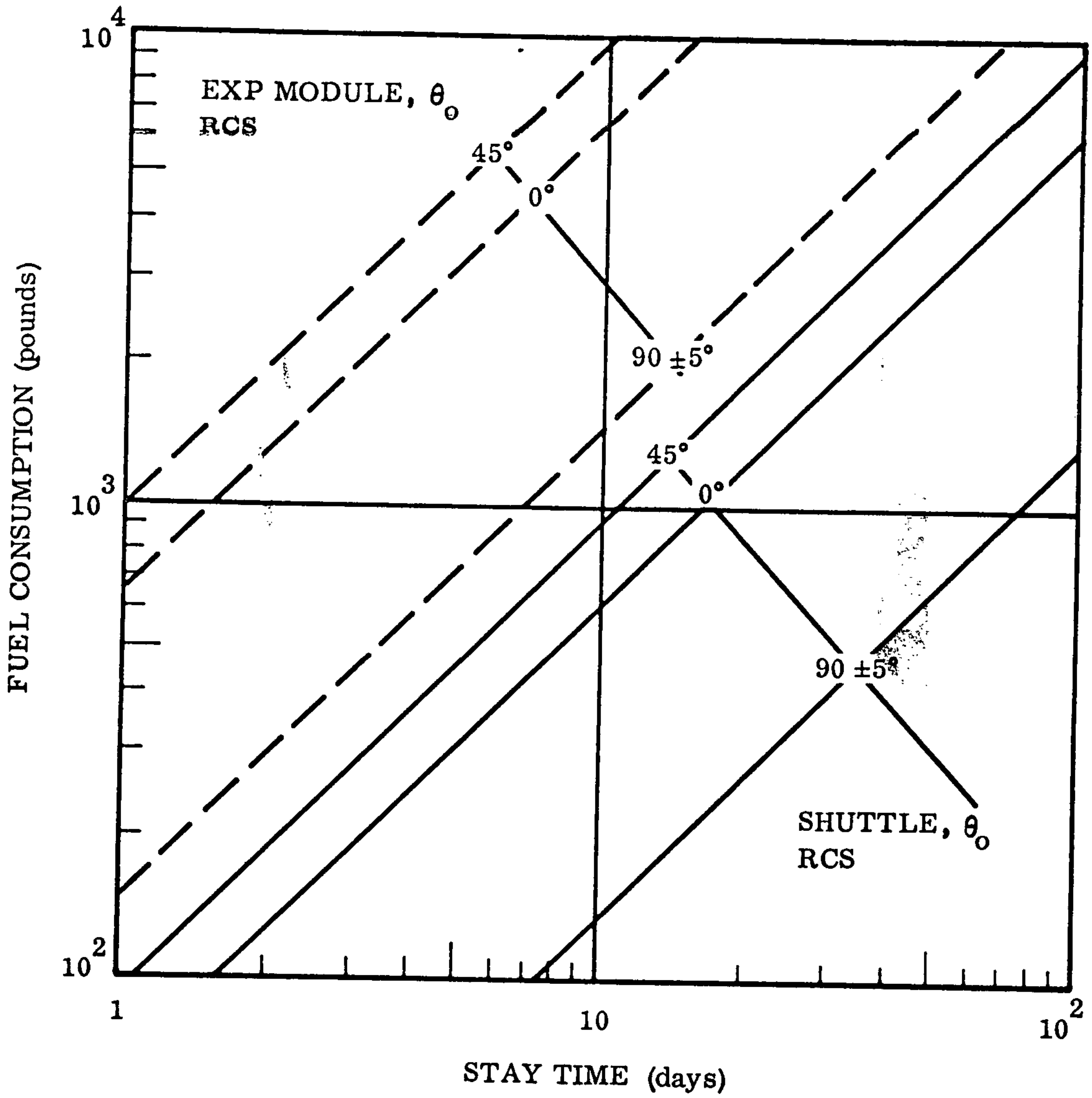

Figure 3-10. Estimated Fuel Requirement for Inertial Orientations Using Either Shuttle or Experiment Module RCS

Table 3-6. Shuttle-Attached Orientation Drivers

Driver	Operating Concept	Desired Orientation
Experiment Earth Surveys (Typical)	C	Earth
Module solar panel (5.9/5.x)	C	Face panels to sun
Module radiator operation	All	Shuttle belly to sun. Earth orientation is acceptable
Module line-of-sight to MSFN	All	Earth is best. Others could be used

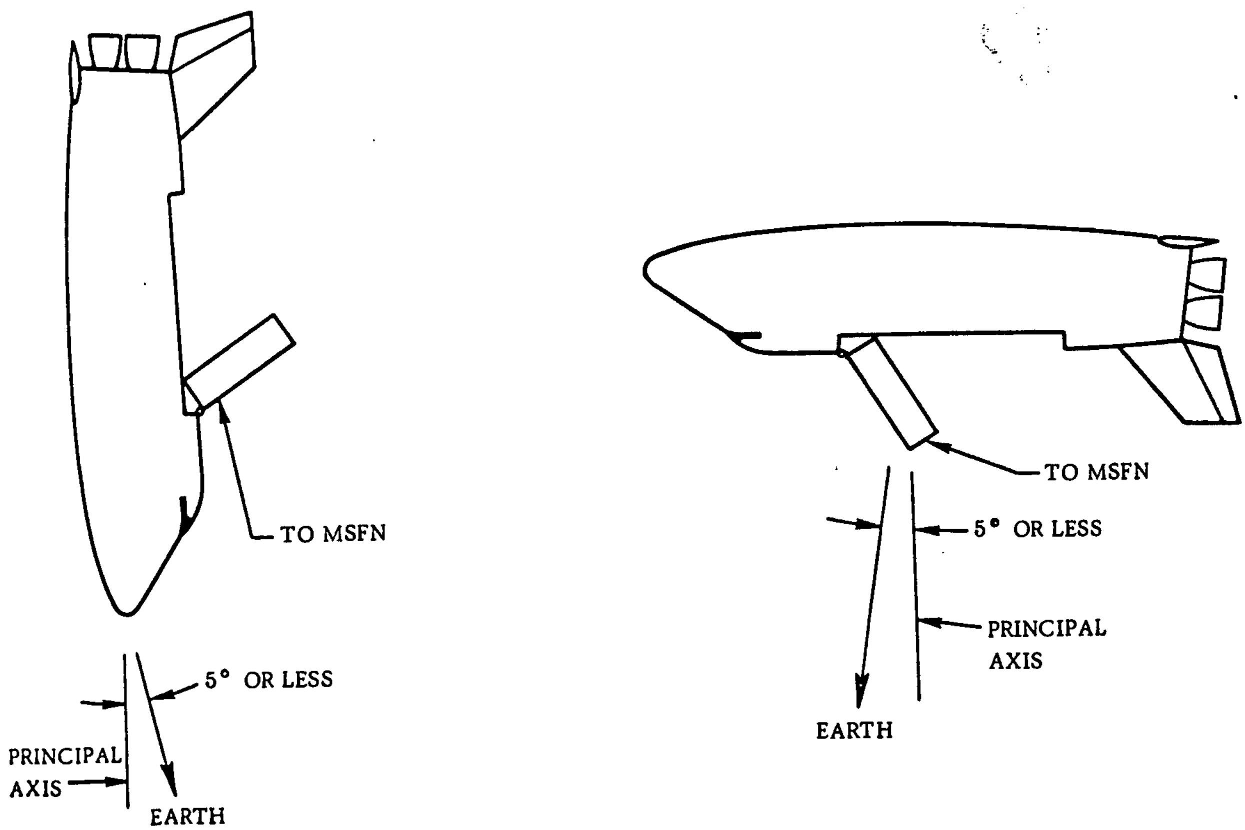

Figure 3-11. Shuttle-Attached Earth-Bound Orientations

Figure 3-12 illustrates an inertial orientation (neglecting orbit normal and sun-earth line motion) in which it is possible to obtain suitable panel and cockpit orientation relative to the sun. The inert orientation restricted ±8 deg relative to the orbit normal yields the same fuel consumption as the earth-bound with ±5 deg restriction. Note that when the earth is directly below the shuttle, communication from module antennas is blocked. A shuttle belly-mounted antenna would clear this problem.

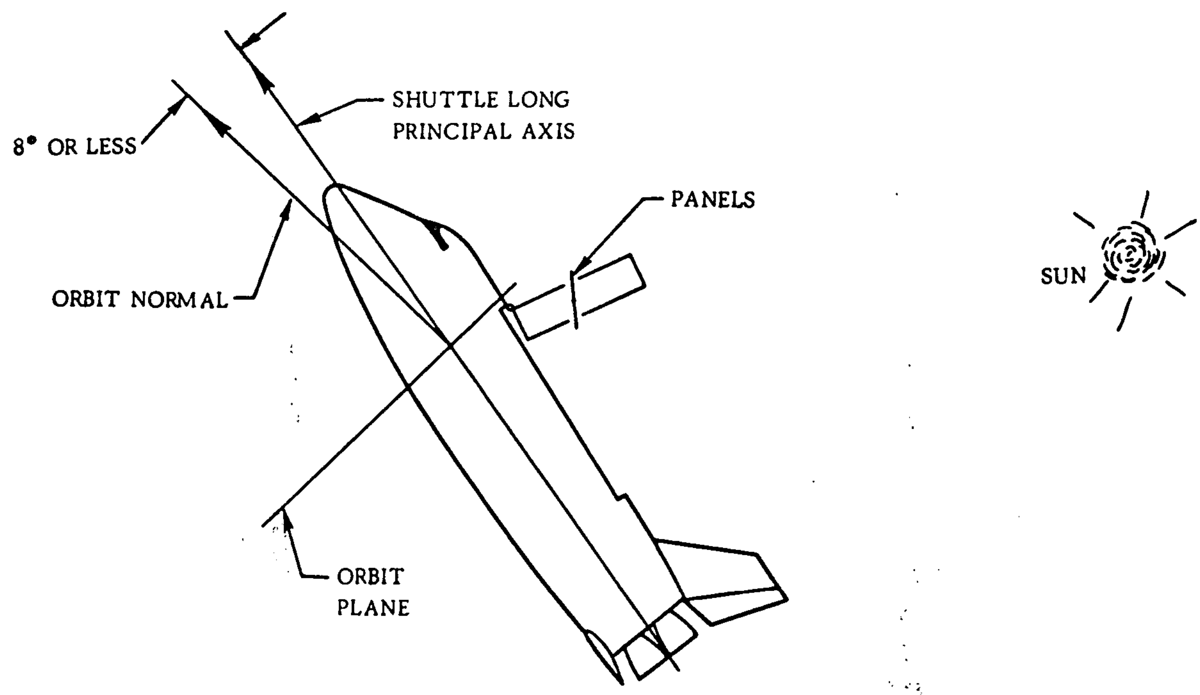

Figure 3-12. Shuttle Attached Inertial Orientation

Table 3-7 gives the limit cycle, environment, and total fuel consumption for relevant accuracy levels.

Table 3-7. Fuel Consumption,† Restricted Shuttle Orientations

Accuracy (± deg)	Fuel (lb/day) Limit Cycle Shuttle	Limit Cycle Module	Environment Shuttle	Environment Module	Total Shuttle	Total Module
0.25	800	40	24	250	824	290
0.5	400	20	24	250	424	270
1.0	200	10	24	250	224	260
2.0	100	5	24	250	124	255
5.0	40	2	24	250	64	252

† For 5 deg or less misalignment in earth reference or 8 deg or less in inertial misalignment

From Table 3-7 it appears that for attitude hold at less than about ±1.0 deg it is desirable to use the experiment module thrusters. Otherwise the shuttle RCS should be used. The largest fuel consumption rate is about 250 lb/day; high-accuracy experiments are limited to about 5 days unless fuel resupply is provided.

The above tabulated total fuel consumption is plotted on Figure 3-13. As shown, a crossover point at about 1 deg attitude accuracy exists. For more stringent accuracy requirements the module thrusters should be used. For less stringent requirements (most of the time) the shuttle thrusters should be used. For comparison purposes Figure 3-13 also shows the effect of a shuttle thruster force level of 150 lb in place of the current 1500 lb level. With this level available, fuel consumption is significantly reduced.

3.3.3 EXPERIMENT MODULE DORMANCY ATTITUDE CONTROL. For the dormant operating period, ±5 deg attitude hold capability is regarded as adequate. However, an added requirement for Biology (5.9/10) and Aeromedicine (5.13/14/15) is that the maximum g level for an experiment hardmount is 2×10^{-3} g or less.

3.3.3.1 RCS Concept Evaluation. Table 3-8 lists the roll and pitch/yaw moments of inertia, the limit cycle fuel rate, and the minimum impulse angular rate for the module experiment installations having a dormant operating mode. As before, it was assumed that the roll thrust level would be adjusted to yield the same fuel rate in roll as in pitch and yaw. The fuel rates shown indicate that the limit cycle fuel is negligible. The angular rates, caused by the minimum impulse thruster firing, are noted to be quite low.

Table 3-8. RCS Limit Cycle Fuel Rate for Dormant Periods (±5 deg)

FPE	Inertia ($Slug-ft^2$) Roll	Pitch/Yaw	Fuel (lb/day)	Angular Rate (deg/sec)
5.9/5.10	29.1k	114k	2.5	0.0054
5.11	30.2k	143.9k	2.03	0.0044
5.13/14/15	36.1k	152.1k	1.92	0.0041
5.22	30.2k	180.3k	1.62	0.0035

From Table 3-8 the approximate average of the pitch/yaw inertias is about 145k $slug-ft^2$. For simplicity, this value is used to compute propellant fuel required to react gravity gradient in either inert or earth-fixed orientations exactly as was done previously for the shuttle-attached configuration. The result is given in Figure 3-14 and indicates that fuel consumption is within current capacity limits (about 2500 lb) regardless of the orientation chosen for mission times exceeding the projected maximum of 60-day periods. There are, of course, the preferred orientations described previously.

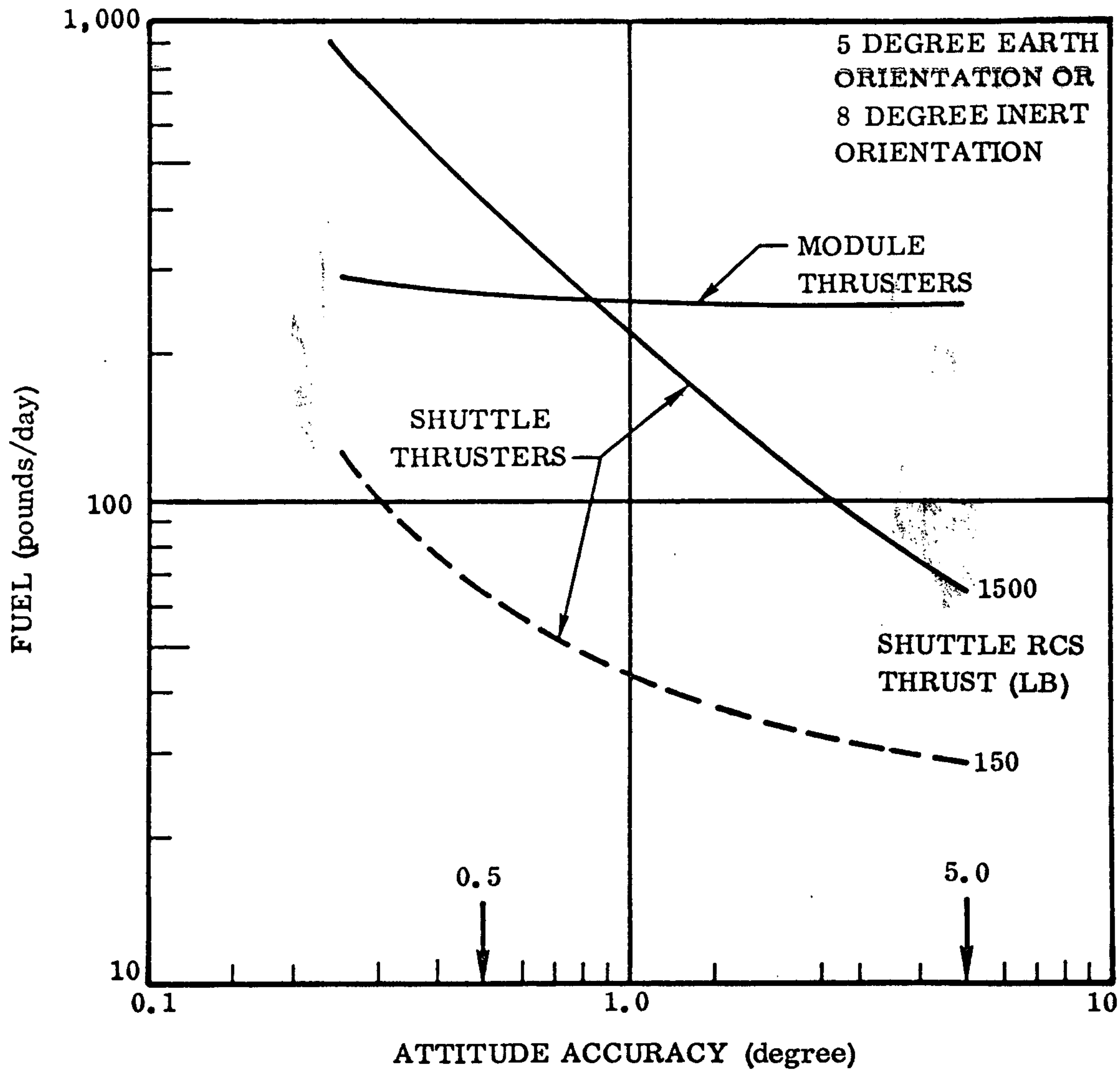

Figure 3-13. Fuel Consumption, Shuttle Versus Module Thrusters (Module Attached to Shuttle)

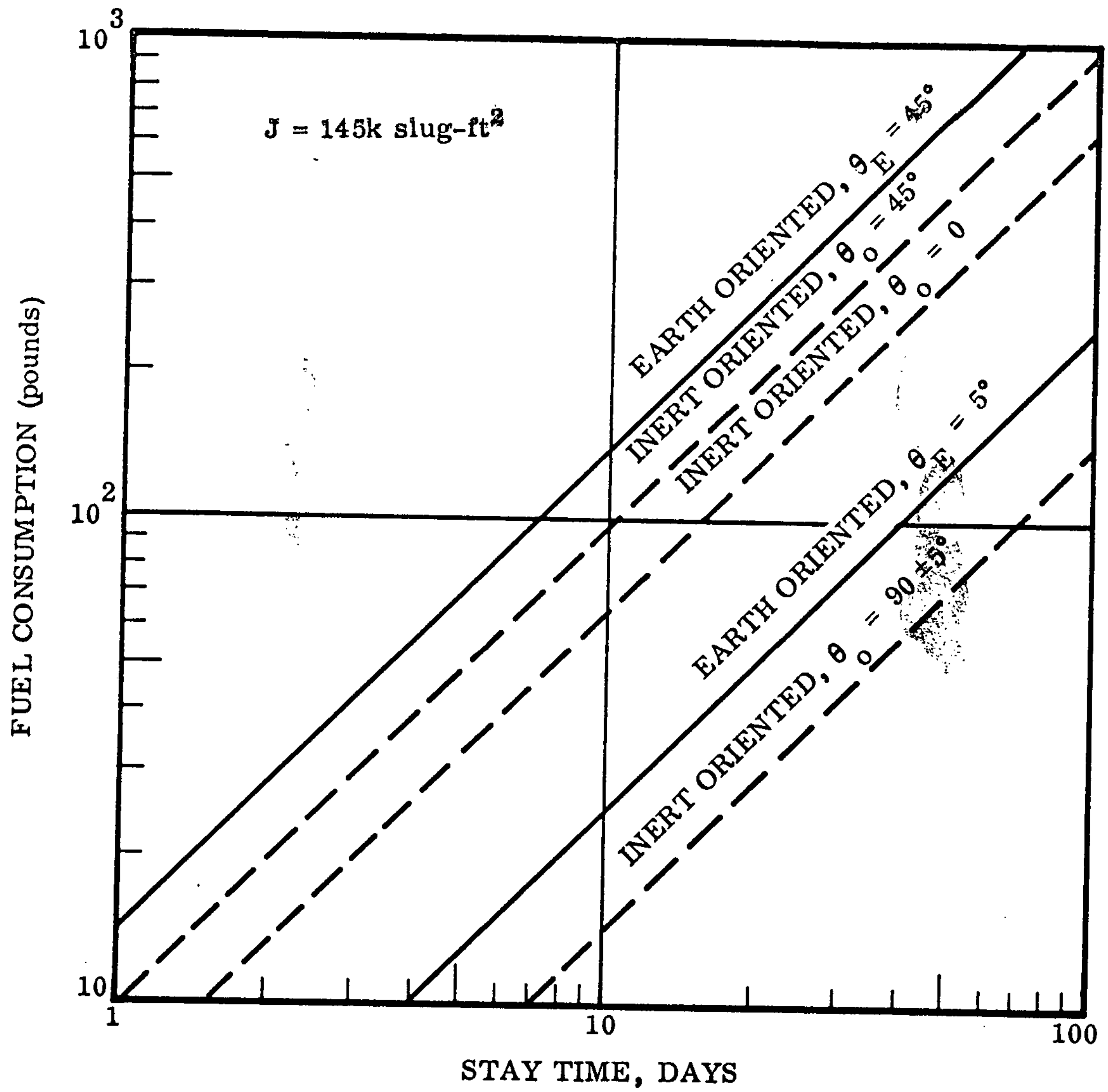

Figure 3-14. Estimated Fuel Requirement for Earth and Inert Orientation for Module Dormant Operating Mode

3.3.3.2 Gravity Gradient Stabilization. Gravity gradient could be used to stabilize the dormant module in an attitude of alignment of the module long axis with earth vertical. The restoring torque is weak (less than 0.01 ft-lb/deg) and a damper is needed to eliminate the natural oscillation at $\sqrt{3}$ times orbit frequency. (From Reference 1, a magnetic anchored damper consisting of about a 20-inch-diameter sphere weighing 150 lb provides damping of this oscillation to 37% (1/e) in 2.5 days.)

Because of its passive character, this system has some appeal. However, the weak attitude hold coupled with low damping makes this system attractive only for much longer mission times with spacecraft containing passive payloads (no on-board perturbation sources).

3.3.3.3 Dual Spin. Primarily to serve as a basis of comparison to the all-RCS system, a preliminary sizing of an alternate technique using a flywheel augmented by either the magnetic torquing bar or hydrazine RCS system of the free flying common module was performed. The flywheel plus magnetic torquer scheme was taken from Reference 2.

The flywheel is sized based upon limiting the drift angle caused by applying the maximum average gravitational torque over one-quarter of an orbit. After this time the magnetic torquer bar can be used to apply compensating impulse thereby returning the spacecraft to its original position. The cycle is repeated. As mentioned previously, either the magnetic torquer or RCS could be used. However, the RCS can be used anytime whereas the magnetic torquer can only be used effectively when the earth field is in proper position. This condition, for an inclined orbit, should occur four times per orbit (page 4-34 of Reference 3).

The maximum average gravitational torque is,

$$T_{gam} = (3/4)\ W_o^2\ J \tag{6}$$

where T_{gam} is the maximum average gravity torque, ft-lb

W_o is the orbit angular rate, 1.1 rad/sec

J is the spacecraft maximum inertia, slug-ft^2

The drift angle accumulated over a quarter orbit is,

$$\theta_d = \frac{\pi\ T_{gam}}{2H\ W_o} = \frac{3\ \pi\ W_o J}{8H} \tag{7}$$

Where H is the flywheel angular momentum, ft-lb-sec

θ_d is the average drift angle over 1/4 orbit, rad

For a drift angle of 5 deg and inertia of 145k slug-ft^2.

$$H = 1.48 \times 10^{-2} \ J = 2140 \text{ ft-lb-sec} \tag{8}$$

This flywheel is about the same size as that within the ATM 2-deg-of-freedom CMG. This flywheel weight was estimated in Reference 2 at 240 lb. Based upon a 0.25 magnetic torquing duty cycle, a compensating torque of 0.5 ft-lb delivered four times per orbit is required. As sized in Reference 3, this torque can be obtained from a 350-lb bar electromagnet. A total weight of over 600 lb results when appropriate electronics, etc., are added. This weight does not become competitive with the all-RCS system (see Figure 3-14) unless the dormant period exceeds 3-6 months depending on module orientation.

The magnetic torquer weight can be traded off with use of the hydrazine RCS. Reacting out accumulated impulse (using the full I_{sp} of 220 sec because of the longer burn time) yields a propellant rate of 3.44 lb/day. This rate is generally lower but of the same order as those given previously for various module orientations on Figure 3-14.

It is emphasized that the above sizing analysis is approximate. The RCS system, however, is shown as suited to the relatively short term dormant mode barring special preferences by the particular mission.

3.3.4 MAINTAINABILITY EFFECTS. The shuttle-only operating mode has a major effect on the redundancy recommended for the free-flying module stabilization and control subsystem. This is expected because of the greater expense involved in an extra shuttle trip for repair (about \$4 M) as compared to that for return to the space station (about \$0.1 M). The added weight, size and power are 400 lb (18.8%), 24.8 ft^3 (34%) and 37 watts (4.0%). The percentage figures quoted apply to the most complex installation, the 3-meter telescope (FPE 5.2). The major components added are an additional CMG and reaction wheel.

3.3.5 REFERENCES

1. G. S. Nurre and P.C. Weygant, "Application of Gravity Gradient Stabilization to Large Manned Space Vehicles," Proceedings of the Symposium on Gravity Gradient Stabilization, 12/3-5/1968, SAMSO-TR-69-307, Aerospace Report No. TF-0066 (5143)-1.

2. Conceptual Design of a High Energy Astronomy Observatory, NASA TM-53976, 16 February 1970.

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3.4 GUIDANCE AND NAVIGATION SUBSYSTEM

3.4.1 REQUIREMENTS AND GUIDELINES. The effect of shuttle-only operation on the guidance and navigation subsystem has been evaluated in accordance with the following fundamental assumptions:

a. Rendezvous and docking of the experiment module to the support module will only be required by those modules carrying experiments of long duration, or modules that will be stored in space between experiments. Other modules will be carried aloft by the shuttle, operate in an attached mode and return to earth by the shuttle at the completion of the experiment.

b. Free orbiting modules will be carried aloft and initially orbited from the shuttle orbiter.

c. Free orbiting modules will eventually be attached to the space station and therefore will either be placed in the space station orbit or be returned to earth for servicing before being made available to the space station.

d. Shuttle will provide the active electronics for docking.

e. Ground tracking will be utilized for guidance/navigation/experiment programming.

f. Shuttle will not provide for the control/command of free flying experiment modules except for docking.

It has further been assumed that the maneuverability of the shuttle will allow positioning of it within a short distance (less than 10 miles) from any free-flying experiment module, either active or dormant.

Several inconsistencies exist in these ground rules. Since the docking radar must be bore sighted with the docking port, this radar must be mounted on the support module. Thus, the active electronics for docking cannot be entirely provided by the shuttle. Further, during docking operations, orders based on measurements by the docking radar must be generated and sent to the experiment module being docked. Since the shuttle will not provide for control of the module, the crew module must contain a control link to the experiment module (TTC loop) or maneuver orders must be relayed via ground tracking stations.

The rendezvous phase between the shuttle and a free-flying module may be accomplished either from the ground or from the shuttle since the shuttle will carry rendezvous instrumentation as part of its normal equipment. If rendezvous is commanded from the ground, based on earth-borne tracking of both the module and the shuttle, then either the shuttle or the module may be commanded to maneuver into a position from which docking can be accomplished. If the shuttle rendezvous radar is used to characterize the relative orbit of the module, then since the shuttle will not provide for the module command and control, the shuttle must maneuver into position from which docking can be accomplished.

Three possible docking configurations appear feasible:

a. Docking radar and necessary support equipment placed on/in the support module with a corner reflector on the module as in the baseline system.

b. Corner reflector on the support module with the docking radar and necessary support equipment on the experiment module.

c. Docking radar on the support module with the necessary support supplied by the space shuttle.

The last of these three configurations has the least effect on the support module/ experiment module configurations. If the second configuration is used, docking will be completely automatic with no provision for manual override or abort.

3.4.2 SUPPORT MODULE SYSTEM. Neither of the two possible means of accomplishing the rendezvous phase requires any equipment in the support module.

If the first docking configuration listed above is implemented, the support module will have to contain: the laser docking radar; a command computer with approximately a one thousand bit memory; an inertial reference system; a tracking, telemetry, and control loop with the module; and the necessary power supply to operate this equipment.

In the second docking configuration listed above, the support module is required to be fitted with a bore-sighted corner reflector, an inertial reference system, a TTC loop, and the necessary power supply to operate the latter two units. These units assure roll alignment of the support module/experiment module at docking.

In the third proposed docking configuration, the only equipment required on the crew module is the docking radar, bore-sighted with the docking port, and the necessary power to support the unit. This configuration will require "hard wiring" the support module to the shuttle in order that the shuttle computer, inertial reference, and TTC loop could be utilized to calculate docking correction orders and transmit such orders to the experiment module. This configuration is recommended since it minimizes both the impact on the baseline experiment module configuration and the amount of equipment required in the support module.

3.4.3 COMMON MODULE REDEFINITION. The major impact of shuttle-only operation on the various common modules will be to remove all equipment concerned with rendezvous and docking from those modules which will operate only in an attached mode and will be returned to earth with the shuttle upon completion of each experiment flight.

Since the shuttle will have the maneuver capability to move to a position within a few miles of a free-flying module (either operating or dormant), the radar transponder suggested for the baseline experiment module system could be removed from the configuration. If, however, the operation of the module is expected to be transferred to a space station when such is available, the transponder will be needed and therefore it is recommended that it be retained in the shuttle-only configuration.

If either the docking system recommended in the last section is adopted, or all docking support equipment is included in the support module, no change in the baseline experiment module is necessary to support the docking phase. If, however, the docking radar is to be placed aboard the experiment module, the function of docking order calculation must also be taken over by the module. This will then require an increase in the size of the experiment module computer and an increase in the size of the power supply in order to meet the requirements of the laser docking radar and the increased computer.

3.4.4 RECOMMENDED SYSTEM. It is recommended that existing shuttle equipment be used to support the shuttle-only module operations. If this is done, shuttle-only operation will have no impact on the baseline experiment module guidance and navigation subsystem. Further, the only equipment required on the support module for rendezvous and docking will be a laser docking radar.

3.5 PROPULSION/REACTION CONTROL SUBSYSTEM

3.5.1 SUPPORT AND EXPERIMENT MODULE - IMPACT. The major requirements on this subsystem for the shuttle-only operating case are discussed under Stabilization and Control Subsystem. The implementing hardware is integral to the baseline experiment modules and no subsystem requirements aboard the support module are identified.

3.5.2 PROPELLANT AND PRESSURANT RESUPPLY. The propellant and pressurant can be resupplied to the experimental module by the shuttle or support module vehicle by fluid transfer through an umbilical line or by replacing the tanks. The fluids were to be transferred through fluid lines from the space station to the module. The approach was reappraised with respect to the use of the shuttle in the absence of the space station.

3.5.2.1 Fluid Transfer. The total capacity of the propellant tanks for the RCS is currently specified as 2560 lbm. A hydrazine resupply system to be placed on the shuttle or support module vehicle is represented in Figure 3-15. The hydrazine onboard the logistics vehicle is stored in a spherical tank with a positive-expulsion bladder. A helium pressurization system is used to effect the transfer. The flow control of the liquid propellant is aided by the use of a cavitating venturi during the transfer process.

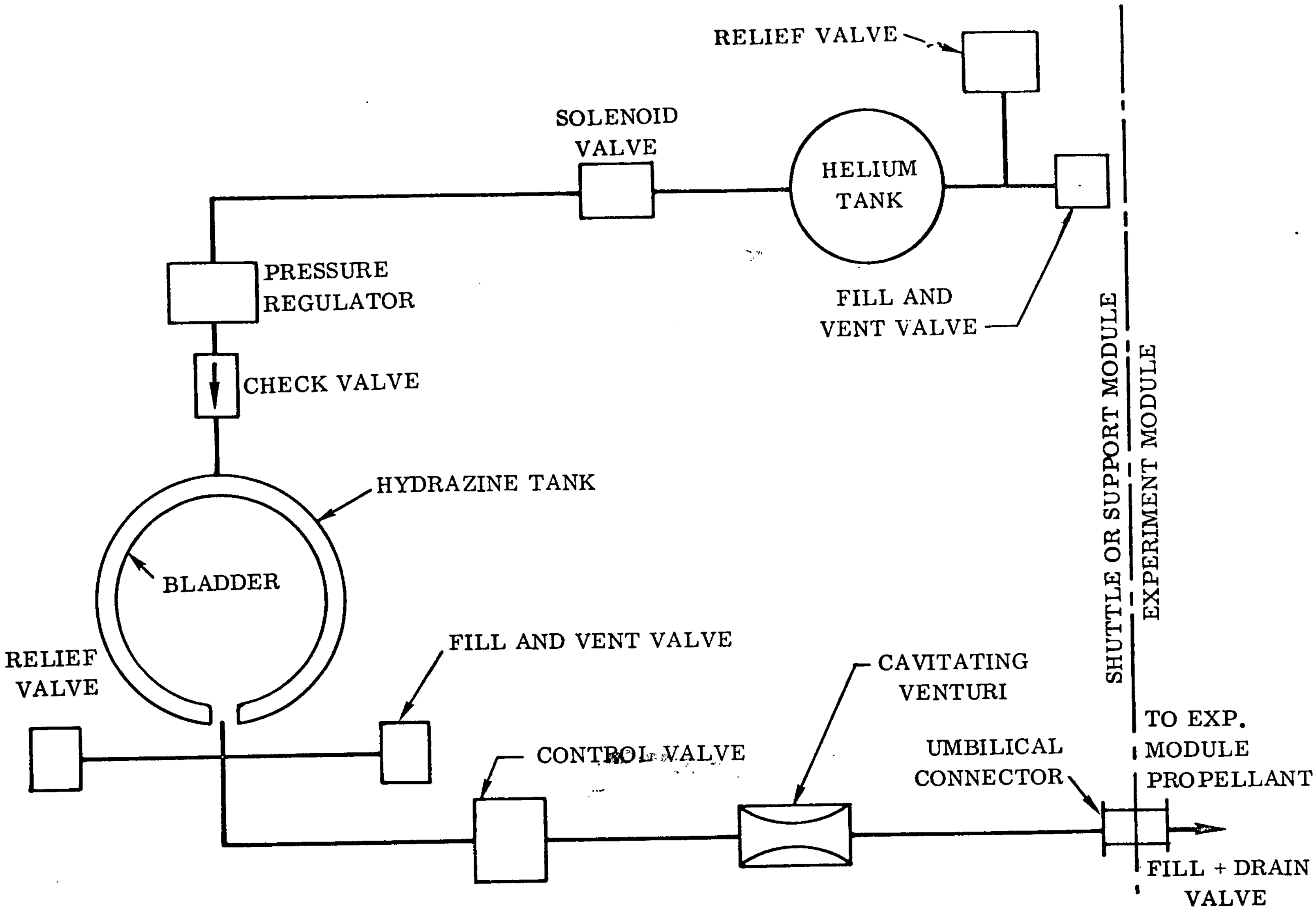


Figure 3-15. Hydrazine Resupply Equipment

This approach is quite simple and no serious developmental problems are anticipated. The umbilical connection would be accomplished in a vacuum environment and any minor leaks would not be serious. The propellant tanks in the experiment module could be depressurized for the transfer process for the purpose, and the associated pressurant dumped overboard.

A simple system that could be placed on the shuttle or support module vehicle to replace the helium pressurant in the module tank is shown in Figure 3-16. Cold helium gas is supplied to the experiment module from an insulated bottle in the support vehicle. When the pressures between the two tanks become equalized, heat is applied to the supply tank to increase the pressure and drive out some of the residual gas into the receiver tank. The transfer process is initially controlled by a pressure regulator, and later by a control valve.

The use of a cold supply gas approach has two basic advantages. The cooling of the receiver tank to remove the heat of compression can be avoided. This transfer procedure and design of the receiver tank system is thereby simplified. In addition, the size and weight of the supply tank could be substantially reduced by this approach. This approach is simple and no serious development problems are anticipated.

3.5.2.2 Tank Transfer. Transfer of 2560 lbm of hydrazine propellant by a man transporting individual tanks is not considered practical. In order to make tank weight compatible with the ability of a man to handle mass in space, roughly 35 tanks have to be provided. The number of disconnections, connections, and checkout items that have to be made would be very time consuming. In addition, the added tank system weight, cost, and complexity to accomplish this are considerable.

The transfer of high pressure gas vessels is not as difficult; a two- to four-tank system would be involved. However, the mechanical manipulations involved in replacing high pressure vessels is substantially greater than in making an external umbilical connection. In addition, the hazzard potential is inherently lower in the fluid transfer approach compared to manipulating the high pressure vessel in a space environment.

Propellant and pressurant transfer resupply from the support module by umbilical line to the experiment module RCS tanks is the selected resupply approach because of less inherent hazard potential, substantially reduced man-in-space servicing time, and commonality with the space station — experimental module designs and operations.

3.6 COMMUNICATION/DATA MANAGEMENT SUBSYSTEM

The situation is examined where both the free-flying and attached modules do not rely on the space station for experiment control, reception of transmitted experiment and subsystem data, and logistic support. Instead, the functions are fulfilled by a support

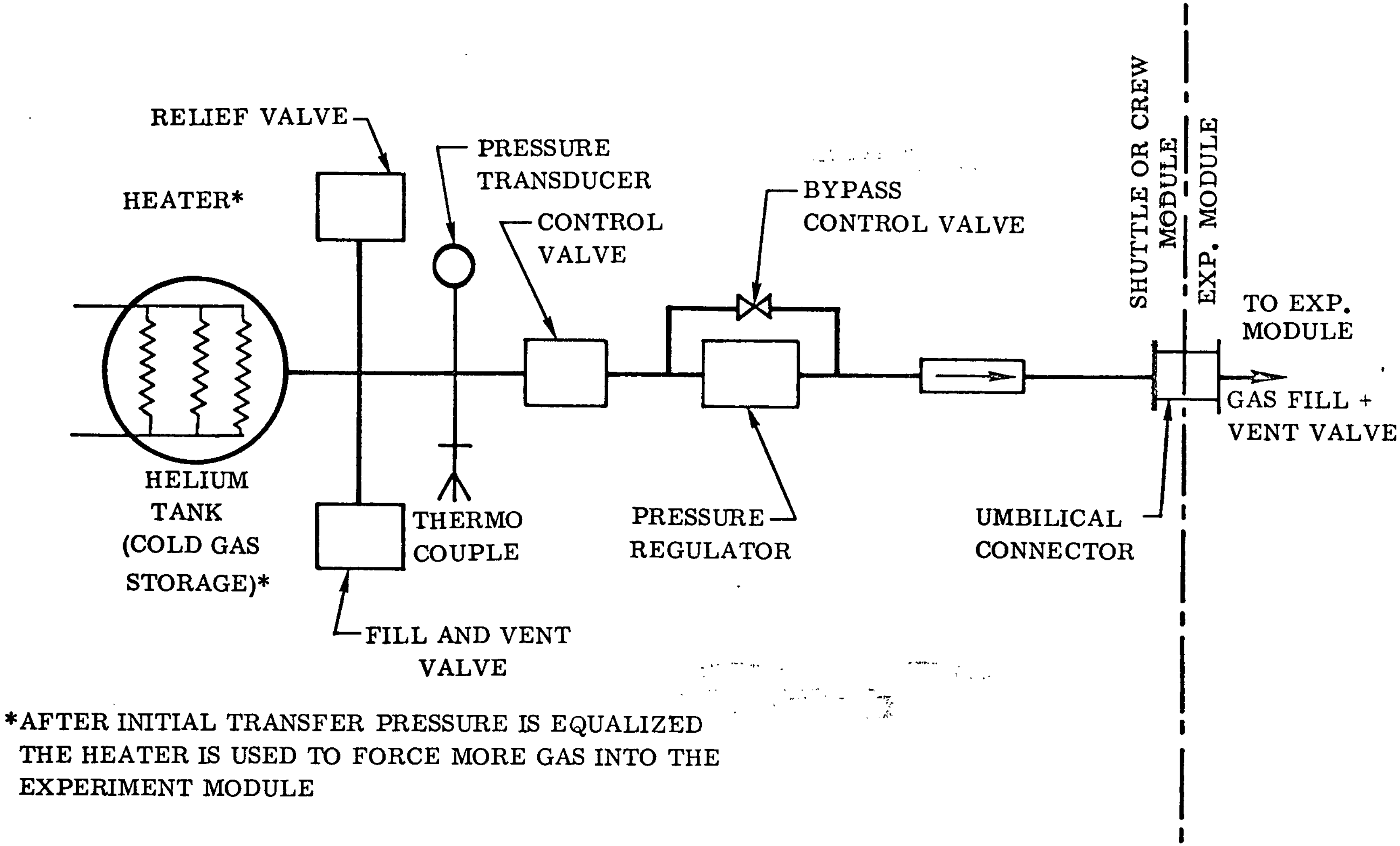


Figure 3-16. Helium Resupply Equipment

module and/or ground station support. The support module is an additional program element required to operate experiment modules for the shuttle-only operating period. Its purpose is basically to perform an interim support role in lieu of the space station while hard-mounted to a shuttle orbiter.

The four module/shuttle concepts A, B, C, and D require examination in terms of the impact on the current experiment module baseline, and of providing the appropriate communications/data management subsystem (CDMS) capability either by kit additions to the experiment modules or through the support module.

The philosophy used in establishing the requirements of shuttle-only operation are shown in Table 3-9.

Table 3-9. Shuttle-Only Operations Ground Rules

Experiment Module

Experiment data transmitted to ground and/or recorded (Concept A)

Experiment data hardlined to support module (Concepts B, C)

Experiment and subsystem control from ground (Concept A)

Laboratory bay for control and displays retained (Concepts B, C, D)

Support Module

Requires recorders for experiment data not transmitted (Concepts B, C)

Required R/W storage, wideband transmitter and antennas (Concepts B, C)

Voice hardline interface with shuttle and experiment module (Concepts A, C)

TT&C RF interface with undocked experiment module (Concepts A, C)

Life Support Kit (Concept D)

Requires recorders for experiment data not transmitted

Requires R/W storage, wideband transmitter and antennas

Voice hardline interface with shuttle

Additional subsystem monitoring and control

3.6.1 DATA TRANSMISSION ALTERNATIVES. Three alternatives exist for transmitting experiment data to the ground for the shuttle-only case.

a. Relay via data relay satellite system (DRSS) with minimum permanent on-board storage.

b. Direct transmission to manned space flight network (MSFN) stations with both permanent and temporary on-board storage.

c. On-board storage with subsequent retrieval by shuttle return.

Figure 3-17 shows parametrically the transmitter power required on the module as a function of data rate for DRSS relay and for direct MSFN links. The case of direct transmission to the space station is also shown for comparison purposes. Assumptions regarding these links appear in Tables 3-10 and 3-11 respectively. It should be noted that for K-band transmission to the DRSS, a 4.5-ft tracking antenna and 10 watts transmitter power are required for 1 Mb/s data rate (100 watts for 10 Mb/s). As a consequence, S-band transmission direct to MSFN is more desirable if data rate requirements do not exceed 10 Mb/s since the complications of a tracking antenna on the module can be avoided. In addition, the prime power requirements from the electrical subsystem are minimized; e.g., 400 + watts (DRSS) versus 12.8 watts (MSFN).

For shuttle-only operation therefore, experiment and subsystem data transmission from the experiment modules will be to the MSFN by ground rule. As a result, continuous data dump is not possible since the ground stations are not always in view. In each of the four concepts shown, the experiment modules must therefore transmit at a much higher rate and/or store a significantly larger portion of the data than in the case of operation with the space station. Since use of MSFN has been selected as the baseline for shuttle-only operation (DRSS is assumed not to be operational at this phase) two forms of additional on-board storage are necessary for the experiment modules: (1) permanent, which is retrieved by shuttle return, and (2) temporary (read/write) which accumulates the data during the experiment for later transmission to convenient ground stations.

Since there will be a number of modules on orbit (270 n.mi.) simultaneously all in the same orbit plane, the question of module spacing or separation must be considered. This is due to the restrictive beamwidth of the MSFN ground station antenna. These antennas are 30 ft in diameter and have a beamwidth of 1 deg at 2.2 GHz. Two situations may prevail: (1) widely separated modules in which case the ground antenna must be slewed to the appropriate acquisition angle after completion of a pass, and (2) closely spaced modules such that two or more are within the one degree antenna beamwidth. In the first case sufficient time must be allowed between module data acquisitions to complete a pass (11 minutes max.) and to reposition the antenna (≈ 2 minutes). This would require module spacing to be approximately 50° thus permitting 7 modules to be accommodated. In the second case, if two or more modules are to be in a common beamwidth (1°) at 270 n.mi. altitude, they must be spaced within 4.7 n.mi.

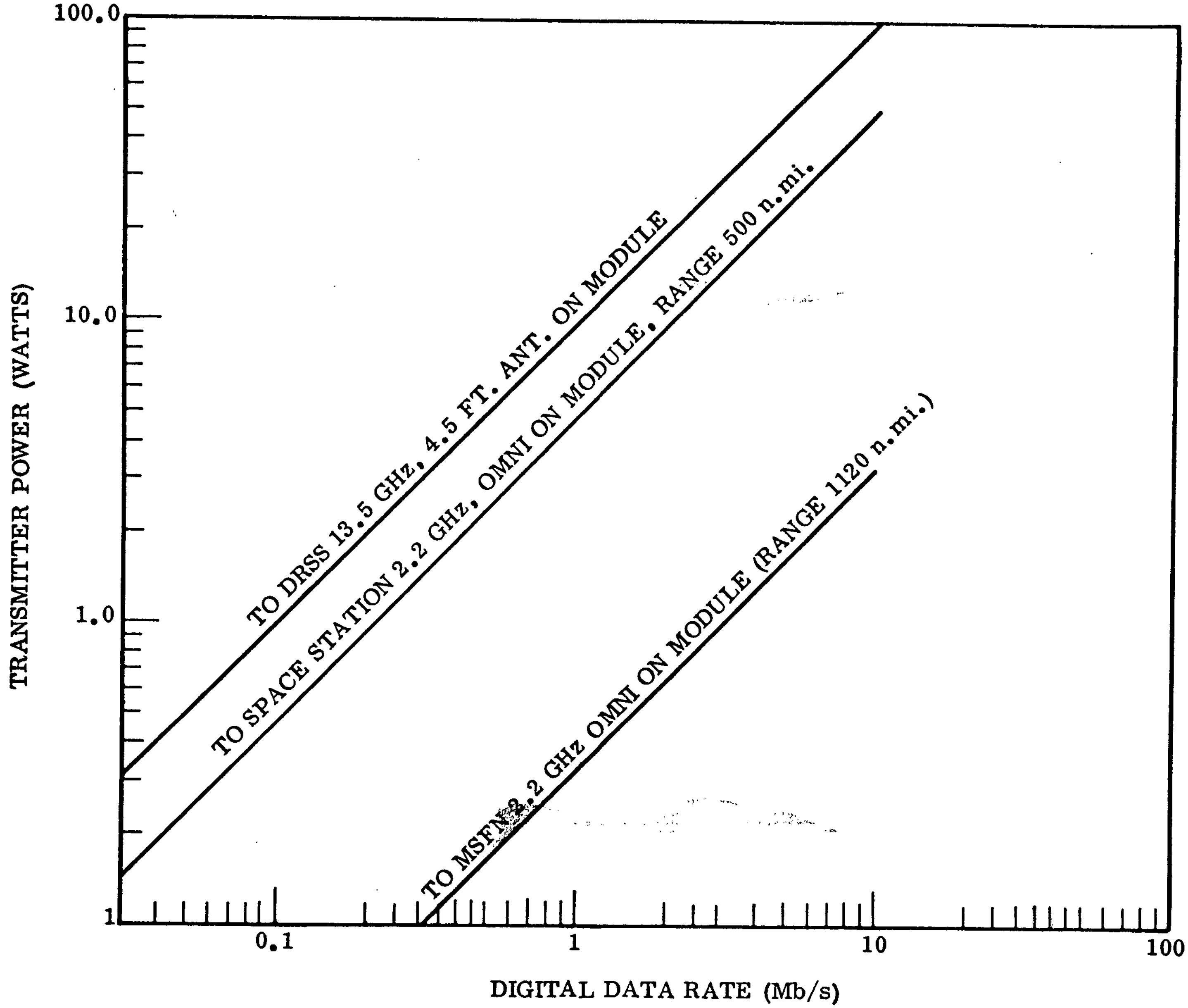


Figure 3-17. Required Module Transmitter Output Power Versus Digital Data Rate

Table 3-10. CM-to-DRSS Digital Data Link (Carrier Frequency 13.5 GHz, 10 Mb/s Data Rate)

CM transmitter power (100 watts)	+ 20.0 dBw
Line loss	- 0.9 dB
CM antenna gain	+ 43.0
Free space loss (23,000 n.mi., 13.5 GHz)	-207.6
DRSS antenna gain (4.5 ft)	+ 43.0
Line loss	- 2.0
Required input signal level for saturated output	-104.5 dBw
Noise Power Density Contribution of Repeater	
Boltzmann's constant	-228.6
Repeater noise temperature (2300°K)	+ 33.6
Repeater Gain (for 6w output)	+112.3
Transmitter antenna gain	+ 30.0
Free space loss (21,000 n.mi., 14 GHz)	-207.1
Atmospheric attenuation	- 2.0
Ground antenna gain (85 ft dish, 14 GHz)	≈+ 54.0
Noise power density	-207.8 dBw/Hz
Noise Power Density Contribution of Ground Station	
Boltzmann's constant	-228.6
Ground receiving system noise temperature (150°K)	+ 21.8
Noise power density	-207.8 dBw/Hz
DRSS to Ground	
DRSS transmitter power (6w)	+ 7.8 dBw
DRSS antenna gain	+ 30.0
Free space loss (21,000 n.mi., 14 GHz)	-207.1
Atmospheric attenuation	- 2.0
Ground antenna gain (85 ft dish, 14 GHz)	≈+ 54.0
Received signal level	-117.3 dBw
Noise power for 10 MHz bandwidth	-134.8
Received SNR	+ 17.5 dB
Required SNR (BER = 10^{-6})	12.5
Margin	+ 5.0 dB

Table 3-11a. Module-to-MSFN Digital Data Link (Carrier Frequency 2250 MHz, 10 Mb/s Data Rate)

Transmitter power (3.2 watts)	+ 5.0 dBw
Line loss	- 1.5 dB
Module antenna gain (omni)	0
Free space loss (2250 MHz, 1120 n.mi., 5° El)	-165.8
MSFN antenna gain (2250 MHz, 30-ft dish)	+ 44.1
Line loss	- 1.5
Received signal level	-119.7 dBw
Boltzmann's constant	-288.6 dBw/Hz-°K
System noise temperature (110°K 5° El)	20.4 dB-°K
Bandwidth (10 MHz)	70.0 dB-Hz
Noise power	-138.2 dBw
Threshold for BER = 10^{-6}	+ 12.5 dB
Margin	6.0
Required S/N	+ 18.5 dB

Table 3-11b. Comparison with Module to-Space Station Digital Data Link (500 n.mi. Separation, 1 Mb/s)

Transmitter power (5 watts)	+ 7.0 dBw
Line loss	- 1.5 dB
Module antenna gain (omni)	0
Free space loss (2250 MHz, 500 n.mi.)	-158.8
Space station antenna gain (15-ft dish, 2° Beamwidth)	+ 38.0
Pointing loss (off beam allowance)	- 2.5
Line loss	- 1.5
Received signal level	-119.3 dBw
Boltzmann's constant	-228.6 dBw/Hz-°K
System noise temperature (1200°K)	30.8 dB-°K
Bandwidth (1 MHz)	60.0 dB-Hz
Noise power	-137.8 dBw
Threshold for BER = 10^{-6}	+ 12.5 dB
Margin	6.0
Required S/N	+ 18.5 dB

3.6.2 DATA REQUIREMENTS. The FPE assignments to the various concepts are described in Section 2. Of special interest is the case of free-flyers (Concept A corresponds to CM-1) where the experiment data must be transmitted or stored on the experiment module. Consequently the FPEs assigned to Concept A were examined in terms of the amount of on-board storage and data transmission required for CM-1. The drivers were found to be FPE 5.2A and 5.3A-1 and their requirements are listed in Tables 3-12 to 3-17.

One of the drivers in these tables is the requirement to dump data to MSFN at 10 Mb/s imposed by the field image videographic instrument of FPE 5.2A (Table 3-13). In this case the impact of non-continuous data transmission is especially severe since the requirement is to make two observations of 20 minutes duration each, per orbit. Because the allowable transmission time to a ground station is only about 5 min average and the station is not necessarily available for readout of the observation at the proper time, on-board recording is required. On rare occasions there may be as many as three orbits not visible by a ground station. This fact imposes a requirement for 120 minutes recording time prior to data dump. It is therefore recommended that this instrument employ two 1-hour 10 Mb/S recording machines. The recorders would alternate their functions of writing and reading so that while one machine records an image for 5.4 min (10 Mb/s) the other may dump to an available ground station at 10 Mb/s. It is assumed that the image is accumulated over a 20-min observation period and retained for at least 5 min by the instrument.

Another driver although not as severe, is the three channels of 1.3 MHz video required by the video cameras of FPE 5.3A-1 (Table 3-15). In this case a three-track longitudinal recording machine is recommended. The three-tracks are written in parallel during the solar flare observation time and read sequentially at times when ground stations are available and the pass period will be at least 7.5 minutes duration. Here the raw data has been preserved in analog form on tape and may be also transmitted as a video signal using frequency modulation of the transmitter. The resultant RF bandwidth is about 7.5 MHz assuming a modulation index of 1.75.

Several of the FPEs assigned to Concept A have a TV requirement of 2.9 MHz video bandwidth. Using Carson's rule, the corresponding RF bandwidth for a modulation index of 1.75 is 16 MHz. Unfortunately, such a wide bandwidth could not easily be accommodated earlier for the module to space station link because of prime power limitations (it would have required 360 watts prime power); consequently a slow scan (1 frame/second) version with a 1 MHz RF bandwidth was proposed. However because of the increased sensitivity of the MSFN ground stations over the space station receiving system (110°K versus 1200°K as well as lower line losses) the wider bandwidth TV transmission link (2.9 MHz) is attainable. Table 3-18 shows that a good quality picture is possible with a 5 watt transmitter using 16 MHz RF bandwidth.

Thus the same transmitter may be used for either 10 Mb/s biphase PCM or 2.9 MHz FM TV by switching in the respective modulators.

Table 3-12. FPE 5.1 — Grazing Incidence X-Ray Telescope

Instrument	Observation Data Rates	Orbit Duty Cycle	Data/Orbit (T_{orbit} = 95 min)	Data/Day (15 Orbits per Day)	Reels per Day	Weight per 5 Days	Weight per 30 Days	Comments
X-ray polarimeter -- (8-Geiger counter detectors/pulse rate counters)	3 KB/s	⊕		3.24×10^7	Transmit only			⊕ Four experiments performed in sequence over a 10 hour period before changing targets
Status data	2 KB/s	cont.			Transmit only			
X-ray spectrometer -- PM image detector, PM(2) line detector	2 KB/s	⊕		2.88×10^8	Transmit only			
Status data	2 KB/s	cont.			Transmit only			
High-resolution studies	6 KB/x	⊕		6.92×10^7				
Film camera	6 frames/min	10%	57 frames/orbit	355 frames/day	0.1	4 lb	24 lb	8700 frames/1000 ft reel 8 lb/1000 ft reel 35 x 35 mm
Status data	2 KB/s	cont.			0.1			
Solid state detector	*0.1 KB/s	⊕		4.7×10^6				*after processing
Status data	5 KB/s	cont.						

Note: Only one experiment (instrument readout) is performed at a time, therefore the maximum rate is 8 KB/s -- the high-resolution studies experiment.

Table 3-13. FPE 52A — Advanced Stellar Astronomy, 3 Meter Telescope

Instrument	Observation Data Rate	Orbit Duty Cycle	Data/Orbit (T_{orbit}=95 min)	Data/Day (15 Orbits per Day)	Reels per Day	Weight per 5 Days	Weight per 30 Days	Comments
Field image videographic instrument	2 exposures per orbit		2 frames/orbit 3.24×10^9 bits/frame	Transmit only				Transmit to ground station at 10 MB/s for 5.4 min/frame
Field image plate camera 225 mm	1 exposure per orbit		1 frame/orbit		1*			*16 frames/magazine 15 lb/magazine
Field image plate camera 70 mm	1 exposure per orbit		1 frame/orbit		1*			*32 frames/magazine 15 lb/magazine
Spectrograph film camera	2 exposures per orbit		2 frames/orbit		2*			*16 frames/magazine 7 lb/magazine
Spectrograph videographic instrument	2 exposures per orbit		2 frames/orbit 4.21×10^8 bits/frame	Transmit only				Transmit to ground station at 10 MB/s for 0.7 min
Experiment status	≈ 2 KB/s	cont.						Assume analog data is digitized and integrated with other digital data
Television	0.18 MHz	intermittent						Slow-scan TV used during experiment set up

Note: Either field imaging or spectroscopy will be installed at one time.

Table 3-14. FPE 5.3A-1 — 1-1/2 Meter Diffraction Limited Solar Telescope

Instrument	Observation Data Rate	Orbit Duty Cycle	Data/Orbit (T_{orbit} = 95 min)	Data/Day (15 Orbits per Day)	Reels per Day	Weight per 5 Days	Weight per 30 Days	Comments
3 range Echelle spectrograph (3 film cameras 30 mm x 100 mm format)	3 frames per sec (1 per sec per camera)	(b)	1350 frames, (b)		(negl)	---	*3 lb	*3050 frames/1000 ft reel 8 lb/1000 ft reel 35 mm film
Hydrogen-alpha videograph (35 mm x 160 mm)	1.3 MHz analog, (a)	(b)	(b)	(b)	Transmit only			Tape for subsequent transmission to ground
White light monitor TV vidicon (25.4 mm x 25.4 mm, 20 lines per mm)	1.3 MHz analog, (a)	(b) (c)			Transmit only			Tape for subsequent transmission to ground
U-V videograph	1.3 MHz analog, (a)	(b)	(b)	(b)	Transmit only			Tape for subsequent transmission to ground
Magnetograph (limited data available)	assume 10 frame/min at 1.2×10^8 bits/frame (a)	(b)	assume 70 mm film 75 frames/obs. (b)	(b)	(negl)	(negl)	*8 lb	*1800 frames/500 ft reel, 8 lbs/500 ft reel, 70 mm x 70 mm

(a) Solar flare event duration 7.5 minutes

(b) Average solar flare occurrence rate one per month, minimum spacing one week

(c) Also used for telescope guidance during experiment set-up at higher frame rate such that the video bandwidth is 2.9 MHz.

Table 3-15. FPE 5.3A-2 — 0.25 Meter XUV Spectroheliograph Normal Incidence Solar Telescope

Instrument	Observation Data Rate	Orbit Data Cycle	Data/Orbit (T_{orbit}=95 min)	Data/Day (15 Orbits per Day)	Reels per Day	Weight per 5 Days	Weight per 30 Days	Comments
Film camera 70 mm x 504 mm format	assume 1 frame/min	50%	47.5 frames/ orbit	71.25 frames/day	0.118*			*605 frames/1000 ft reel 16 lbs/1000 ft reel 70 mm film
Boresighting TV camera	0.18 MHz	Inter-mittent						Slow-scan TV used during experiment set-up

Table 3-16. FPE 5.3A-3 — Solar Coronagraph

Instrument	Observation Data Rate	Orbit Duty Cycle	Data/Orbit (T_{orbit}=95 min)	Data/Day (15 Orbits per Day)	Reels per Day	Weight per 5 Days	Weight per 30 Days	Comments
1 to 6 solar radii (18 mm x 24 mm format)	assume 5 frames/min	50%	240 frames/ orbit		1			Used 35 mm film 3600 exposures/magazine 8 lb/magazine
5 to 30 solar radii 20 mm x 24 mm	assume 5 frames/min		240 frames/ orbit		1			Use 35 mm film 3600 exposures/magazine 8 lb/magazine

Table 3-17. FPE 5.3A-4 — 0.5 Meter X-Ray Solar Telescope

Instrument	Observation Data Rate	Orbit Duty Cycle	Data/Orbit (T_{orbit} = 95 min)	Data/Day (15 Orbits per Day)	Reels per Day	Weight per 5 Days	Weight per 30 Days	Comments
Film camera, 35 mm			6 frames/orbit		0.7			128 exposures/magazine 5 lb per magazine
Vidicon, image storing type	3.24×10^8 bits/frame		1 frame/orbit	Transmit only				Transmit at 1 MB/s for 5.4 min
Spectrometer	9.5×10^8 bits/frame		1 frame/orbit	15 frames per day	10	80 lb	480 lb	Record on digital film. 1.44×10^9 bits/100 ft x 70 mm. 1.6 lb per 100 ft.

Table 3-18. CM-to-Ground TV Link Power Budget (Carrier Frequency 2263 MHz, Video Bandwidth = 2.9 MHz)

CM transmitter power (4.6 watts)	+ 6.6 dBw
Line loss	- 1.5 dB
CM antenna gain (omni)	0
Free space loss (2263 MHz, 1120 nmi, 5° El)	-165.9
MSFN antenna gain (2263 MHz, 30-ft dish)	+ 44.1
Line loss	- 1.5
Received signal level	-118.2 dBw
Boltzmann's constant	-228.6 dBw/Hz-$^\circ$K
System noise temperature (110°K at 5°El)	+ 20.4 dB-$^\circ$K
*Bandwidth (16 MHz)	+ 72.0 dB-Hz
Noise power	-136.2 dBw
FM improvement threshold	+ 12.0 dB
Margin	+ 6.0
Required S/N	+ 18.0 dB
Min. predetection S/N (improvement threshold)	+ 12.0 dB
Peak-peak/rms factor	+ 9.0
**FM improvement (β = 1.75)	+ 14.0
Video S/N (pk-pk/rms)	+ 35.0 dB

*$B_{IF} = 2f_m(1 + \beta)$

**$R = \frac{3}{2} (\beta^2) \frac{B_{IF}}{f_m}$

It should be noted that current MSFN ground stations have a capability of only 200 Kb/s with no plans for extending this capability*. For shuttle-only operations and space station operation with no DRSS, some MSFN ground stations will have to be modified to support the experiment module program, and this modification must include both a 10 Mb/s and a video/analog (16 MHz RF) capability. The power budget for CM-1, for a 10 Mb/s data link to an S-band MSFN ground station, is shown in Table 3-10.

3.6.3 SUPPORT MODULE SYSTEM. For Concept A (CM-1) and Concepts B and C (CM-3 and -4) a support module is required as a space station substitute. The complement of communications and information management equipment in the support module necessary for Concept A is different than for Concepts B and C. Data transmission and recording equipment is carried on the module for Concept A whereas in Concepts B and C this equipment is located in the support module. The compelling reason for this arrangement is that the shuttle will not stay on orbit for those experiments associated with Concept A. Consequently, the Concept A module must operate independent of the support module.

Since the support modules must operate in conjunction with all types of modules (docking for maintenance of detached modules, etc.), it is more cost effective if one support module design accommodates both attached or detached modules. Consequently, the support module communications and information management subsystem is designed with permanent storage digital and video tape recorders, temporary read/write, digital and video tape machines, a wideband transmitter, and omni antennas as shown in Figure 3-18. The driver for sizing the data transmission rate from the crew module is the growth version of FPE 5.11, the attached earth surveys module, where the bandwidth could increase to approximately 10 MHz for a high resolution TV system. A command transmitter and telemetry receiver is included in the baseline for receiving telemetry from the transmitting commands to detached modules of Concepts A and C. Table 3-18a lists the equipment complement required for the support module.

3.6.4 FREE-FLYER (CM-1) REDEFINITION. As mentioned earlier in the data requirements discussion some reconfiguration of the CM-1 free-flyer baseline is required for shuttle-only operation. This reconfiguration in the form of both temporary read/write and permanent data storage is due primarily to the non-continuous nature of the data transmission link to the MFSN ground stations. Table 3-19 lists the equipment required for free-flying modules (Concept A) as well as for other module types. Note that the listing for Concept A includes an additional amount of redundant equipment (primarily recorders and a computer operated data bus channel). This amounts to an increase of about 100 lb relative to the system defined for space station operation. This of course is due to the increased cost of a shuttle repair trip relative to the space station repair operation.

*Current planning is to support high data rate programs such as the space station with DRSS. Eventually many MSFN stations will be deactivated when and if DRSS becomes operational.

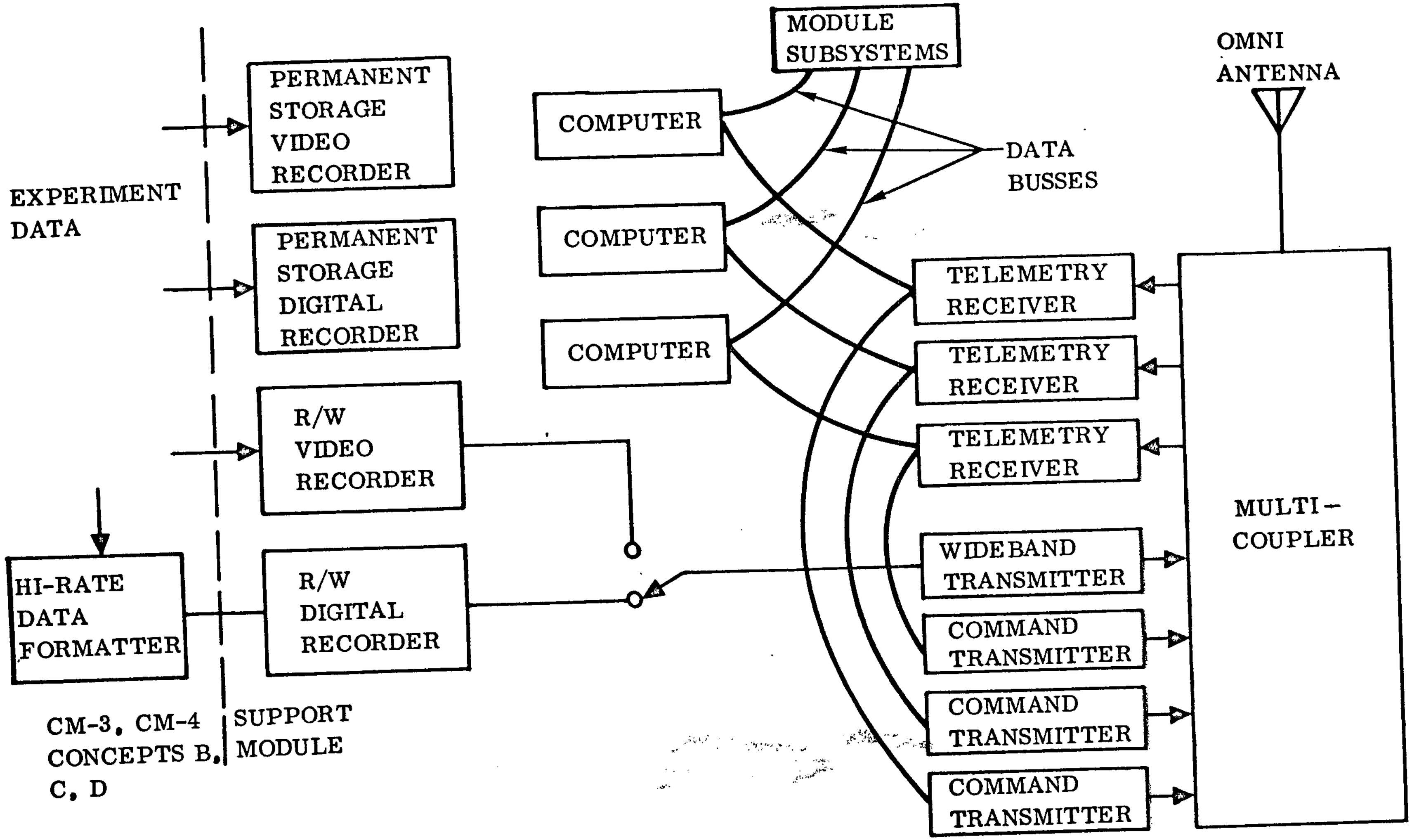


Figure 3-18. Support Module Communications and Information Management Subsystem

Table 3-18a. Communications and Information Management Subsystem Support Module Equipment List

Item	Unit Wt-Lb	Quantity
Video tape recorder	35	1
Digital tape recorder	35	1
R/W recorder-video	35	1
R/W recorder-digital	35	1
Computer	8	3
Bus I/F unit	1	12
Data bus	2	3
Wideband transmitter	7	1
Command transmitter	8	3
Telemetry receiver	15	3
Multicoupler	5	1
Omni antenna system	10	1

The increased on-board storage requirements may influence orbit-stay time to some extent; consequently the weight of the required film and tape was estimated for 5 and 30 day missions, respectively. The results are shown in Table 3-20 and were extracted from Tables 3-11 to 3-17.

The free-flying modules (Concept A) will transmit telemetry data to MSFN ground stations as well as receive commands from these stations. Tables 3-21 and 3-22 show the power budgets for these two links and indicate adequate margin exists for a 1-watt transmitter aboard the module.

Turn-around ranging capability was provided in the baseline for a pseudo-noise ranging or Goddard range and range rate systems for backup rendezvous and docking capability. This capability is also useful for module tracking from MSFN stations and consequently the link power budget for this mode is included in Table 3-23.

3.6.5 ATTACHED MODULE (CM-3 AND CM-4) REDEFINITION. For shuttle-only operation the additional permanent and temporary data storage for attached modules CM-3 and CM-4 (Concepts B and D) is contained in the support module. Since these modules effectively never leave the shuttle/support module — they are brought up to orbit by the shuttle, remain attached, and are returned by the shuttle — there is no need for transmitters, receivers, and antennas. This equipment is furnished in the support module. Table 3-19 reflects these changes.

Table 3-19. Communications and Information Management Subsystem Experiment Module Equipment List

Item	Unit Weight (lb)	Quantity per Concept			
		A	B	C	D
TV camera	5	3	1	1	1
High rate formatter	5	3	1	1	1
Low rate formatter	2.5	2	1	2	1
Video tape recorder (1)	35	1			
Digital tape recorder (2)	35	2			
R/W recorder (video)	35	2			
R/W recorder (digital)	35	2			
Command decoder	2	5	1	3	1
Computer	8	4	1	3	1
Bus I/F unit	1	32	9	23	9
Data bus	2	4	1	3	1
Wideband transmitter		2			
TT&C transmitter	8	2		3	
TT&C receiver	15	3		3	
Remodulator	2	3		3	
Multicoupler	5	1		1	
Omniantenna system	10	1		1	
Control/display console (3)	50		1	1	1
Hard copy storage (3)	50		1	1	1
TV monitor (3)	50		1	1	1

Notes: Quantities include redundancy for module recovery for those modules that have rendezvous and docking capability (Concepts A and C). For Concept A, the listing includes additional redundancy to permit experiment continuation after failure.

(1) Longitudinal recording machine to support FPE 5.2A only.

(2) Transverse recording machine to support FPE 5.3A only.

(3) Laboratory bay equipment may be omitted on some attached modules.

Table 3-20. Tape and Film Weight Summary vs FPE

FPE	Weight (5-Days)(lb)	Weight (30-Days)(lb)
5.1 X-Ray	4	24
5.2A Stellar	70 - 150	420 - 900
5.3A Solar	599	2592

Table 3-21. CM-to-MSFN Telemetry Link (Carrier Frequency 2287 MHz, 10 kbps Telemetry Data Rate)

CM transmitter power (1 watt)	0 dBw
Line loss	-2.5 dB
CM antenna gain (omni)	0
Free space loss (2287 MHz, 1120 nmi, 5° el)	-167.6
MSFN antenna gain (2287 MHz, 30-ft dish)	+ 44.1
Line loss	-2.5
Received signal level	-128.5 dBw
Modulation loss	-2.4 dB
Received subcarrier level	-130.9 dBw
Boltzmann's constant	-228.6 dBw/Hz °K
System noise temperature (110°K, 5° el)	+ 20.4 dB °K
Bandwidth (10 kHz)	+ 40.0 dB-Hz
	-168.2 dBw
Subcarrier S/N	+ 37.3 dB
Required S/N for BER = 10^{-6}	(-) + 12.5
Margin	+ 24.8 dB

Table 3-22. MSFN-Ground-to-CM Command Link (Carrier Frequency 2106 MHz, 100 bps Command Rate)

Ground transmitter power (1 kw min)		+ 30 dBw
Line loss		-2.5 dB
MSFN antenna gain (30-ft dish)		+ 43.0
Free space loss (2106 MHz, 1120 nmi, 5° el)		-166.2
CM antenna gain (omni)		0
Line loss		-2.5
Received signal level		-98.2 dBw
Boltzmann's constant		-228.6 dBw/Hz $^{\circ}$K
System noise temperature (1200°K)		+ 30.8 dB $^{\circ}$K
Predetection bandwidth (16 kHz)		+ 42 dB-Hz
Noise power		-155.8 dBw
Predetection S/N		+ 57.6 dB
Subcarrier modulation loss (β = 1.2, r = 0.38)		-3.7
FM improvement factor (β = 1.2)		+ 13.5
Postdetection S/N		+ 67.4 dB
E/N_o (in a 100 Hz bandwidth)		+ 47.4 dB
Required E/N_o for BER = 10^{-6})	(-)	+ 12.5
Margin		+ 34.0 dB

Table 3-23. CM-to-MSFN PRN Ranging Link (Carrier Frequency 2287 MHz, 1 Mbps Code Rate)

CM transmitter power (1 watt)	0 dBw
Line loss	-2.5 dB
CM antenna gain (omni)	0
Free space loss (2287 MHz, 1120 nmi)	-167.6
MSFN antenna gain	+ 44.1
Line loss	-2.5
Received signal level	-128.5 dB
Modulation loss	-21.1 dB
Received PRN level	-149.6 dBw
Boltzmann's constant	-228.6 dBw/Hz °K
System noise temperature (110°K, 5° el)	+ 20.4 dB °K
Code tracking bandwidth (1 Hz)	0 dB-Hz
	-208.2 dBw
PRN S/N	+ 58.6 dB
Required S/N for 30-ft rms noise error	(-) + 32.0
Margin	26.6 dB

0

3.6.6 DORMANT PERIOD COVERAGE (CONCEPT C). In Concept C the module contains a laboratory whose equipment is changed relatively infrequently or whose experiments are carried aboard in suitcase form. Between equipment changes and perhaps between experiments, the module is stored in orbit in a dormant mode. In this case only TT&C (Telemetry, Tracking, and Command) equipment is required to monitor the dormant module's status and to issue appropriate commands. This monitoring and commanding is done using the MSFN. Any experiments that are performed during the dormant period may be monitored in the same manner by using the TT&C link. It is assumed that the experiment data rate in this mode is sufficiently low ($<$ 10 kbps) or data recording/storage is supplied as part of the "suitcase" experiment.

3.6.7 ON-BOARD CHECKOUT. The philosophy established for on-board checkout is that the prelaunch, boost, and on-orbit testing system will be an integral portion of the communication/data management subsystem and as such will provide the capability of testing all subsystems and experiments. Further, the on-board checkout will be performed to the line replaceable unit (LRU) level for detection and display of failures. Isolation to the LRU level is accomplished by implementing within each LRU built-in-test (BIT) logic and stimuli. The communications/information management subsystem computer then initiates and evaluates both LRU and subsystem loop tests.

A preliminary estimate of the number of monitoring points within the subsystems and experiments is 350 (250 engineering subsystems plus 100 experiments). Calibration functions, diagnostic routines, and limit checking will require approximately 1000 words of computer memory.

For free-flying modules, detected failures are telemetered to the ground. Failed LRUs may then be replaced by regular shuttle logistic resupply trips. Note that redundancy was included in critical subsystems as well as experiments to avoid special servicing.

For attached modules, detected failures may abort the mission; therefore, it is conceivable that some spares may be carried aboard the shuttle, support module, or experiment module. This has not been established as an operational procedure since, again, redundancy was included in critical subsystems and may also be included to provide the desired overall reliability for the experiment duration.

3.7 ELECTRICAL POWER SUBSYSTEM (EPS)

Those factors which exert the strongest influence on EPS design for shuttle-only operation of experiment modules are the short mission times of 5 to 30 days for manned operation and the reassignment of the Cosmic Ray Laboratory (FPE 5.8) to a free-flying mode. The shortened mission times result in fuel cells becoming attractive relative to solar cells from a system weight and equipment cost standpoint. Reassignment of FPE 5.8 requires doubling the EPS power rating for the CM-1 module relative to the space station operating mode baseline design for FPE 5.2A.

A fuel cell design has been established for the support module which serves as a space station substitute. This system supplies a nominal one kilowatt for support module loads with three kilowatts available for experiment loads. Batteries are provided in order to meet peak load demands and as safety backup to the fuel cells for operation of the support module EC/LS system after an EPS failure.

The dormancy kit design chosen for the CM-3 and CM-4 modules during unmanned activity is the CM-1 solar panel design supplemented in two instances. One of these is the module containing the space biology experiments which requires full rated power during a maximum shuttle hand-over period of 48 hours (back-to-back operation). The other experiment requiring supplementary fuel cells is the wireless power transmission experiment (FPE 5.24h) which requires 10 kW for unmanned experiment periods up to ten days in duration.

Table 3-24 summarizes each of the EPS designs and identifies pertinent shuttle-only considerations.

3.7.1 FUEL CELL SIZING. The following data is based on the Allis Chalmers 2 kW fuel cell module. This module is 35.2 in. x 16 in. x 20.2 in. (3.3 cu ft) in size, weighs 180 lb and requires 70 watts of parasitic power. Various items of ancillary equipment are required as identified below.

System elements for a support module EPS are depicted in Figure 3-19. Parametric data covering the entire anticipated application range of the 2 kW modules is given in Table 3-25 and in Figure 3-20.

Product water is available at approximately 3.5 gallons/day per fuel cell module operated at its rated capacity of 2 kW.

Total weight is the sum of dry weight from Table 3-25 and reactant weight from Figure 3-20.

3.7.2 LIGHTWEIGHT SOLAR ARRAY TECHNOLOGY. As an alternate to the use of two complete baseline design CM-1 systems for the Cosmic Ray Laboratory an examination was made of the current status of lightweight solar arrays.

Table 3-24. EPS Design Summary

EPS Design	Baseline Xmod Design	Sized By	Shuttle-Only Impact	Resolution
CM-1	Solar Cell 2.4 kw Avg. 7.0 kw Peak	5.2A Stellar	Resize for FPE 5.8	Use two CM-1 systems for FPE 5.8. Use existing design for other FPEs. Growth (hot-mirror) version of FPE 5.2A use two systems. As an alternate use lightweight array techniques. This will result in increased maintenance requirements.
CM-3, 4	Space station dependent 5.0 kw Avg. 7.0 kw Peak	5.8 Cosmic 5.11 Earth Surveys	Support module replaces space station. Dormancy kit installed in some cases.	No change to existing design except to extent necessary to integrate kits.
Support Module	Not in XMOD baseline -- new design for shuttle-only.	5.9 Etc Space Biology 5.11 Earth Surveys	Required as a substitute for space station.	Fuel cell system is lighter than solar cell system for mission operations <30 days and is comparable up to 60 days. Install 4 kW system with batteries for peaking.
Dormancy Kit	New for shuttle-only.	5.9 Etc Space Biology	Required as a partial substitute for space station during unmanned activity.	Solar cell/battery system has capability for > 60 days. Use a "leave-off" tailored version of CM-1 EPS design. For short durations use fuel cells (version of support module EPS).

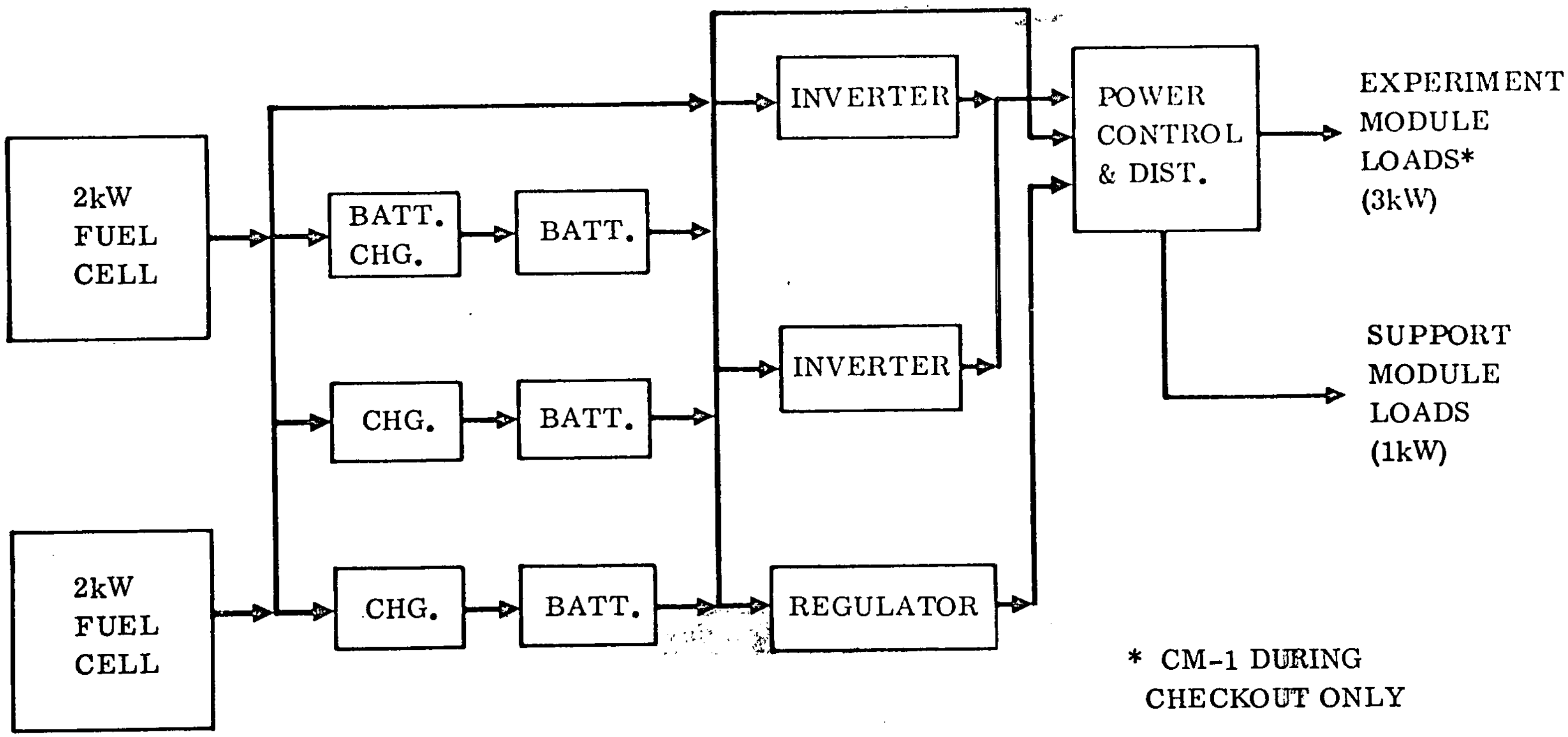


Figure 3-19. Electrical Power Subsystem, Selected Concept, Support Module

Table 3-25. Fuel Cell Dry Weights

Installed Capacity (kW)	2	4	6	8	10	12
Fuel cell module	180	360	540	720	900	1080
Thermal control unit	25	25	30	30	35	35
Product water unit	40	40	45	45	50	50
Control unit	30	30	30	40	40	40
Allowance for radiator, pumps, coolant, etc.	60	120	180	240	300	360
Total dry weight (lbm)	335	575	825	1075	1325	1565

Primary sources of information were a paper presented at the MSFC symposium on Long-Life Hardware for Space* and Hughes Aircraft Company reports on contracts with the USAF.**

Based on these sources a 1000 sq ft roll-up array would weigh between 250 and 350 lb. This size array would meet the CM-1/FPE 5.8 power requirements.

Disadvantages of the roll-up design relative to the discrete panel design are variation in temperature during sunlight/dark transition resulting in variable power, reduced durability, lower frequency and less well damped oscillations with possible interaction with the SCS, and a generally less well developed technology.

3.7.3 RELIABILITY/MAINTAINABILITY. No additions were made to the EPS selected design configuration specifically for reliability optimization beyond that incorporated in the space station operating design, namely:

2 Solar panels	1 Battery charger
1 Motor drive servo amplifier	1 Regulator
1 Battery	1 Inverter

* Boretz, J. E., "Technology Problems Associated with Large Solar Arrays for Long Duration Space Missions," pp. 220-255, Proceedings.

**Contracts AF33(615)-2750 and F33615-69-C-1676.

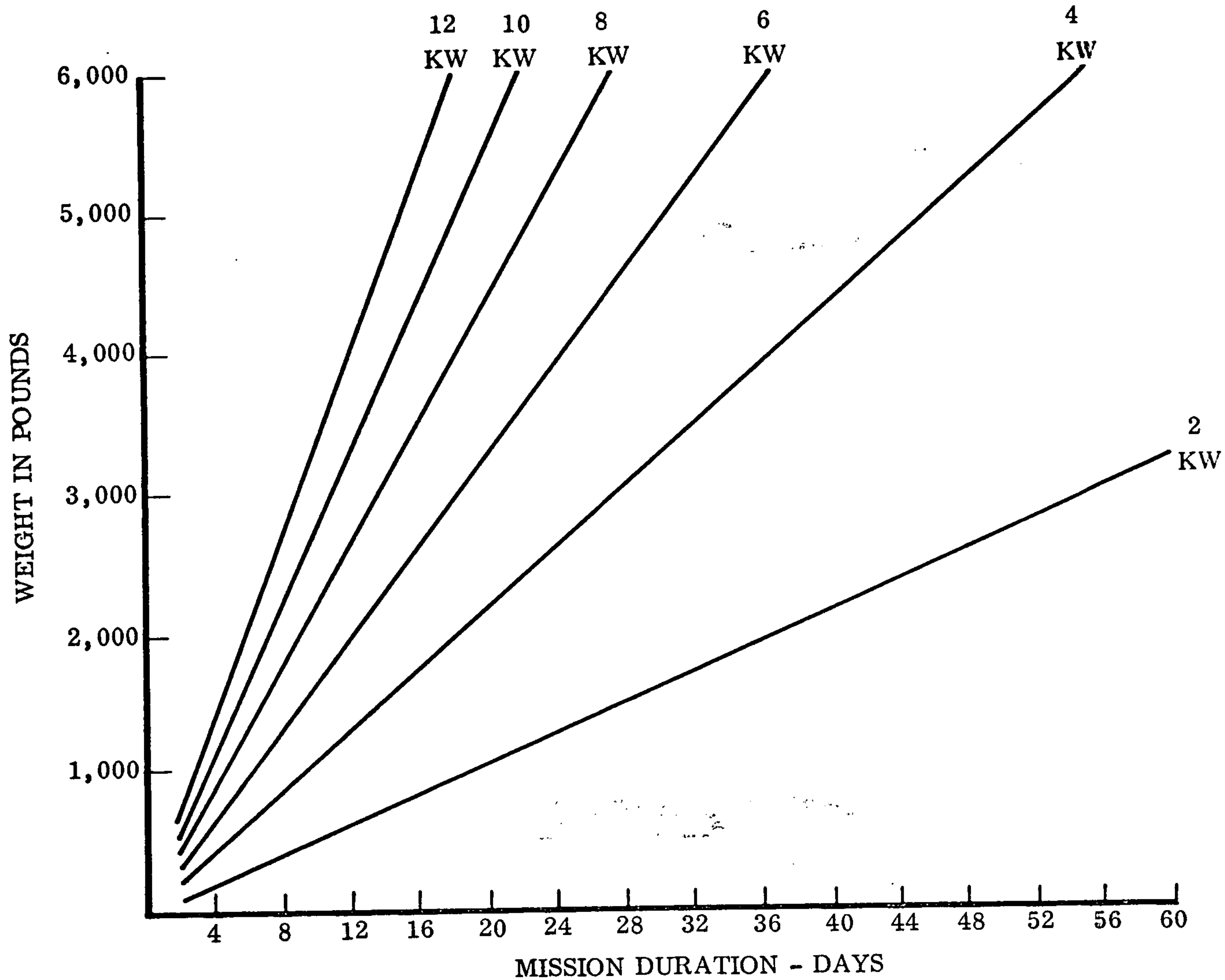


Figure 3-20. Electrical Power Subsystem

These selected additions increase the EPS reliability sufficiently that they are also valid for the shuttle-only operations. This is attributable to the necessarily discrete addition of components resulting, in some instances, in greater reliability than needed.

3.8 THERMAL CONTROL SYSTEM

The thermal control analysis established a cooling system for the support module and a redundancy concept for CM-3 and CM-4 modules when these are left in a dormant mode in orbit.

3.8.1 SUPPORT MODULE SYSTEM. The largest cooling requirement for the support module is obtained when the crew is operating FPE 5.11, Earth Surveys. It was assumed that 1.2 kW of the experiment and subsystem cooling system would be convected into the module atmosphere. This load must be rejected by the support module thermal control system. In addition the TCS must remove the latent and sensible heat from the crew. The total cooling requirement is 5000 Btu/hr. With this sizing criterion the support module can be operated in all relevant modes, Concepts A, B or C.

The critical components are identical with those in CM-1 free-flying module. Table 3-26 lists the weights and volumes for the components. The list includes components for dehumidifying the air, which is not required in CM-1. There are fewer and smaller cold plate cabinets. When the radiators do not supply sufficient low temperature coolant due to degraded thermal operation (shuttle interference or vehicle orientation), a water evaporator is used. Two additional water evaporator systems are included to allow for two failures while retracting the crew module. These units are sized for 1000 Btu/hr with four hours capacity.

A schematic of the support module thermal control system is shown on Figure 3-21. The heat exchangers for the atmosphere and the emergency suits are shown on the schematic, but they are not included in the weights on Table 3-26 as they are EC/LS components.

3.8.2 ATTACHED EXPERIMENT MODULE COOLING SYSTEM. The baseline for the attached CM-3 and CM-4 modules includes a cooling system independent of space station. For the shuttle-only case this system should provide sufficient cooling capacity for modules in Concept B (experiments conducted while attached). However, under Concept C the modules could be left in orbit in a dormant mode. It is necessary to supply redundant cooling systems for this dormant condition to meet initial operational function requirements. Redundant requirements could not be met satisfactorily with some form of add-on equipment and hence the basic system had to be revised. For reasons of commonality, it is preferred that the thermal control system for Concept B should be the same as for Concept C.

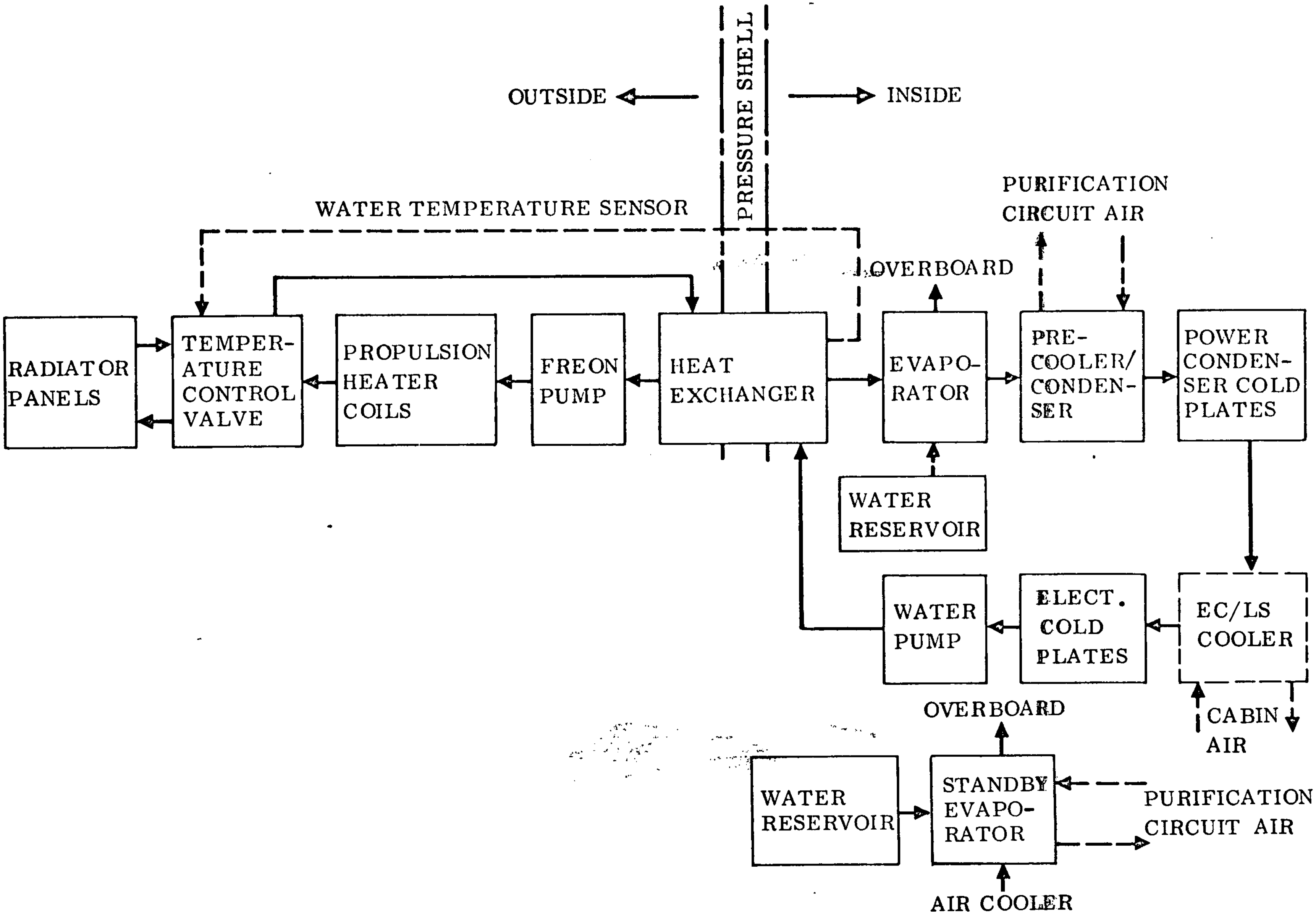


Figure 3-21. Thermal Control Schematic for Support Module

Table 3-26. Thermal Control Components for Support Module

Component	Power (watts)	Volume Ext. (ft^3)	Volume Int. (ft^3)	Weight (lb)
Radiator - 400 Ft^2		9.50		400
Freon pump, motor, accumulator	25	0.25		15
Intercooler		0.50		10
Water pump, motor, accumulator	8		0.25	15
Temp. control, sensors & valve		0.50		20
Evaporator			0.70	10
Cold plate elec. cabinet			5.00	100
Cold plate battery cabinet			5.00	100
Wall insulation		50.00		60
Fluid lines			0.35	25
Water & reservoir			3.80	132
Air precooler			0.50	5
Air dehumidifier			0.70	10
Standby evaporator			0.35	5
Standby water reservoir			0.15	5
TOTAL	33	60.75	16.80	912

Tables 3-27 and 3-28 compare the weights of TCS components in CM-3 and CM-4 for space station requirements versus those resulting from implementation of Concept C dormant mode redundant requirements. The biology experiments, FPE 5.9, installed in CM-3 are the most demanding requiring 2.5 kW[(1)] of cooling while in the dormant mode to sustain animals and plants. This cooling requirement is considerably more than the free-flyer capability under a failure condition which basically requires module recovery

(1) Current closed loop EC/LS operation plus partial automation of experiments during the maximum-assumed dormant period of two days requires above 3 kW. It is assumed that reasonable design changes in the experiment EC/LS involving open loop operation during the dormant mode will drop this power requirement to 2.5 kW.

Table 3-27. Thermal Control Components for CM-3

Component	Space Station Only 4 kW		Shuttle-Only 3-2.5 kW	
	No. Units	Weight (lb)	No. Units	Weight (lb)
Radiator — 600 ft^2		600		650
Freon pump package	2 x 15 lb	30	6 x 15 lb	90
Intercoolers	3 x 10	30	6 x 10	60
Water pump package	2 x 15	30	6 x 15	90
Temperature control	3 x 20	60	6 x 20	120
Fluid lines		35		75
Insulation		120		120
Cold plate cabinet battery	—		1	187
Cold plate cabinet SCS	—		1	197
Cold plate cabinet elec	—		1	197
Total		905		1786

Table 3-28. Thermal Control Components for CM-4

Component	Space Station Only 5.5 kW		Shuttle-Only 3-1 kW	
	No. Units	Weights (lb)	No Units	Weight (lb)
Radiator — 850 ft^2		850		850
Freon pump package	3 x 15 lb	45	3 x 15 lb	45
Intercooler	4 x 10	40	4 x 10	40
Water pump package	3 x 15	45	3 x 15	45
Temperature control	4 x 20	80	4 x 20	80
Fluid lines		50		100
Insulation		228		228
Cold plate cabinet battery	—		1	100
Cold plate cabinet elec.	—		1	100
Total		1338		1588

only. It was assumed that 1 kW of cooling would be sufficient for subsystem operations for dormant operation of CM-4. Therefore, the TCS components of CM-4 need only be operated in three independent loops to achieve a satisfactorily redundant system. Since the radiators on CM-3 use all of the available area, it was necessary to include redundant coolant loops in some of the panels in order to have three independent circuits. All of the components are from CM-1, the free-flyer except the cold plate cabinets provided for the dormant mode of CM-4.

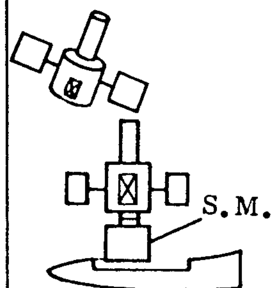
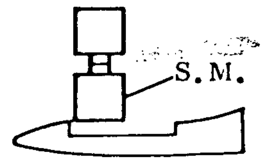
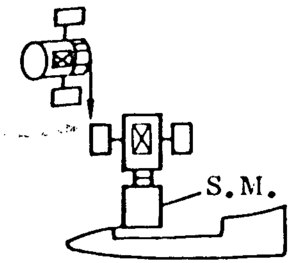
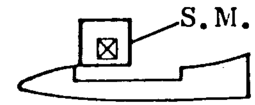
3.8.3 FREE-FLYING EXPERIMENT MODULE COOLING SYSTEM. In order to dissipate the full module thermal load while attached to space station or support module without evaporating water, it is necessary to utilize the maximum radiator area, 460 ft^2. The thermal control system will reject 2.8 kW maximum under this condition and will permit operating the experiment for checkout while docked.

The maintainability analysis conducted on this module, however, indicates that it will be cost effective to build redundancy into the basic module radiator heat dissipation system. This will be accomplished by adding a second independent fluid circuit to the basic vehicle radiator structure along with the associated freon and water pumps, intercooler heat exchanger and the concomitant temperature control hardware. These additions will add 274 pounds to the weight of the module thermal control system.

3.9 ENVIRONMENTAL CONTROL/LIFE SUPPORT

3.9.1 REQUIREMENTS AND GUIDELINES. The major crew support requirements for shuttle-only operation are summarized in Table 3-29. The support module must contain EC/LS equipment to support two men for up to 30 days. In addition, for Concepts A and C, it must supply pressurization gas for the experiment modules to provide a shirtsleeve environment during servicing. For the 30-day missions, payload deductible consumables must be provided on board the shuttle for support of the shuttle crew for 25 days. No major changes are required on the experiment modules for any of the concepts. While the experiment modules are docked to the support module, they will be dependent upon the latter for EC/LS support. In this case, the support module takes the place of the space station in providing the EC/LS functions. For the detached mode of operation, the experiment modules are depressurized and unmanned and require no EC/LS functions. The one exception to this is for the dormant biolaboratory in CM-3, Concept C. This module is left pressurized while dormant, but the maximum time between shuttle visits is two days. For this short period of time no extra EC/LS equipment is required. The existing thermal control equipment will maintain nominal temperature and provisions for CO_2 removal, dehumidification, and O_2 supply are not required because of the absence of the crew. Atmospheric leakage for the two days will be approximately 3% which need not be made up until the support module re-docks with the experiment module.

Table 3-29. Basic EC/LS Requirements for Shuttle Operation

Requirements	Operational Concepts			
	A	B	C	D
Requirements		 EARTH	 ON-ORBIT OR EARTH	 EARTH
Support Module:				
1. Crew size	2	2	2	2
2. Duration (max.)	5 days	30 days	30 days	5 days
3. Must pressurize XMods	yes	no	yes	no
Shuttle:				
1. Crew size	2	2	2	2
2. Duration for which expendables required	0	25 days	25 days	0
Experiment Module:				
Changes required	none	none	none	none

The guidelines of the shuttle-only analysis and design assumed complete independence between the shuttle and the support module EC/LS subsystems. This was necessary because it was assumed that there was no manned passage way between the deployed support module and the shuttle. Thus, fixed hardware equipment aboard the shuttle could not be used to support the crew aboard the support module and vice versa. Also, no atmospheric interconnection or interchange was assumed between the support module and shuttle.

Other relevant study guidelines and criteria are listed below:

a. All occupied compartments:

1. Pressure = 14.7 psia
2. Standard air composition
3. Nominal temperature = 75°F
4. Nominal relative humidity = 50%
5. Nominal CO_2 partial pressure = 3.0 mm. Hg.

b. Compartment pressurized volumes and leakage rates:

	Vol (ft^3)	Leakage (lb/day)
1. Shuttle cabin	1300	4
2. Support module	1100	2
3. CM-1	2100	2
4. CM-3	2100	2
5. CM-4	3270	2

c. Crew data:

1. O_2 consumption	1.84 lb/man-day
2. CO_2 production	2.12 lb/man-day
3. Potable water	6.0 lb/man-day
4. Wash water	4.0 lb/man-day (no shower)
5. Urine produced	3.45 lb/man-day
6. Respiration & perspiration water	3.09 lb/man-day
7. Total metabolic heat output	11,200 Btu/man-day
8. Dehydrated food	1.25 lb/man-day
9. Hydrated food	1.25 lb/man-day

d. Fuel cell weight penalties:

1. Fixed hardware 120 lb/kW
2. Fuel and tankage 1.13 lb/kW-hr

e. Maximum emergency time for retraction of the support and experiment module into the shuttle bay: 4 hr

3.9.2 DESIGN STUDIES

3.9.2.1 CO_2 Removal. Without CO_2 removal, the normal concentration buildup rate in the support module alone would be as shown in Figure 3-22. As can be seen, CO_2 removal is required for both the 5- and 30-day missions. Both LiOH and molecular sieves were considered for this purpose. For the 5-day missions, the use of LiOH is lightest, simplest, cheapest and definitely recommended. For the 30-day missions, a molecular sieve device is also a potential candidate and the two are briefly compared below. These comparisons indicate the LiOH is also favored for 30-day missions.

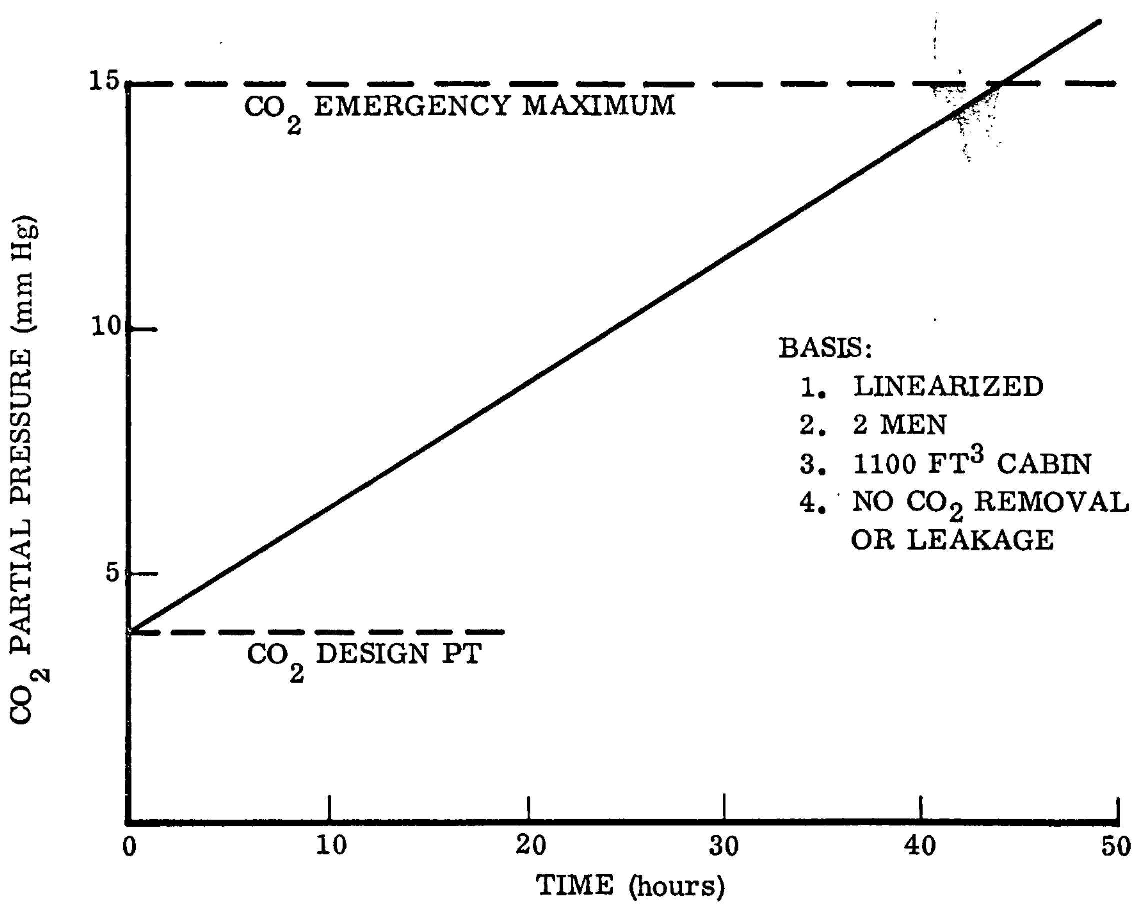


Figure 3-22. Normal CO_2 Buildup Rate in Support Module

Typical properties of LiOH are given in Table 3-30, which gives a weight penalty of 2.8 lb/man-day. An electrically desorbed, water save, molecular sieve was estimated to weigh 100 lb and require 400 watts. This unit would be designed for two men and a cabin CO_2 partial pressure of 3 mm Hg. A similar unit using coolant fluid at 120°F for desorption rather than electrical heaters, and dumping water vapor to space, was estimated to weigh 135 lb and require 50 watts of power for the blower, coolant pump penalty and controls.

The total weight penalties of the molecular sieve units are compared to that for LiOH in Figure 3-23. The fuel cell weight penalties given in Section 3.9.1 have been used and are included in the curves. This graphical comparison is approximate and does not include minor effects such as the heat rejection penalties, the benefit of using the molecular sieve driers for dehumidification, etc. Water balance effects would favor the LiOH but have not been considered in detail because of the presence of the fuel cell power source and the relative abundance of water. As indicated in the figure, the LiOH is favorable on a weight basis for 30 days, and thus becomes heavily favored when other factors are considered. The LiOH system is simpler, less expensive, more highly developed, more reliable and offers commonality with the 5-day mission crew module system as well as the shuttle system.

3.9.2.2 Oxygen and Nitrogen Storage. The oxygen, nitrogen, and storage vessels for these gases are the heaviest EC/LS items for most of the shuttle concepts. The gas is required for breathing, compartment pressurization, and leakage. It is required aboard the support module, aboard the shuttle for operation in excess of five days, and aboard the common module's crew habitability kit.

Table 3-30. Properties of LiOH

1.	Reaction	
	$2\ LiOH + CO_2 = Li_2\ CO_3 + H_2O$	
	48 + 44 = 74 + 18	
2.	CO_2 rate (lb/m-d)	2.12
3.	LiOH reacted (lb/m-d)	2.31
4.	Approximate percentage of LiOH reacted	90
5.	LiOH required (lb/m-d)	2.57
6.	Weight allowance for canister and filters (%)	10
	(lb/m-d)	0.26
7.	Total weight required (lb/m-d)	2.83

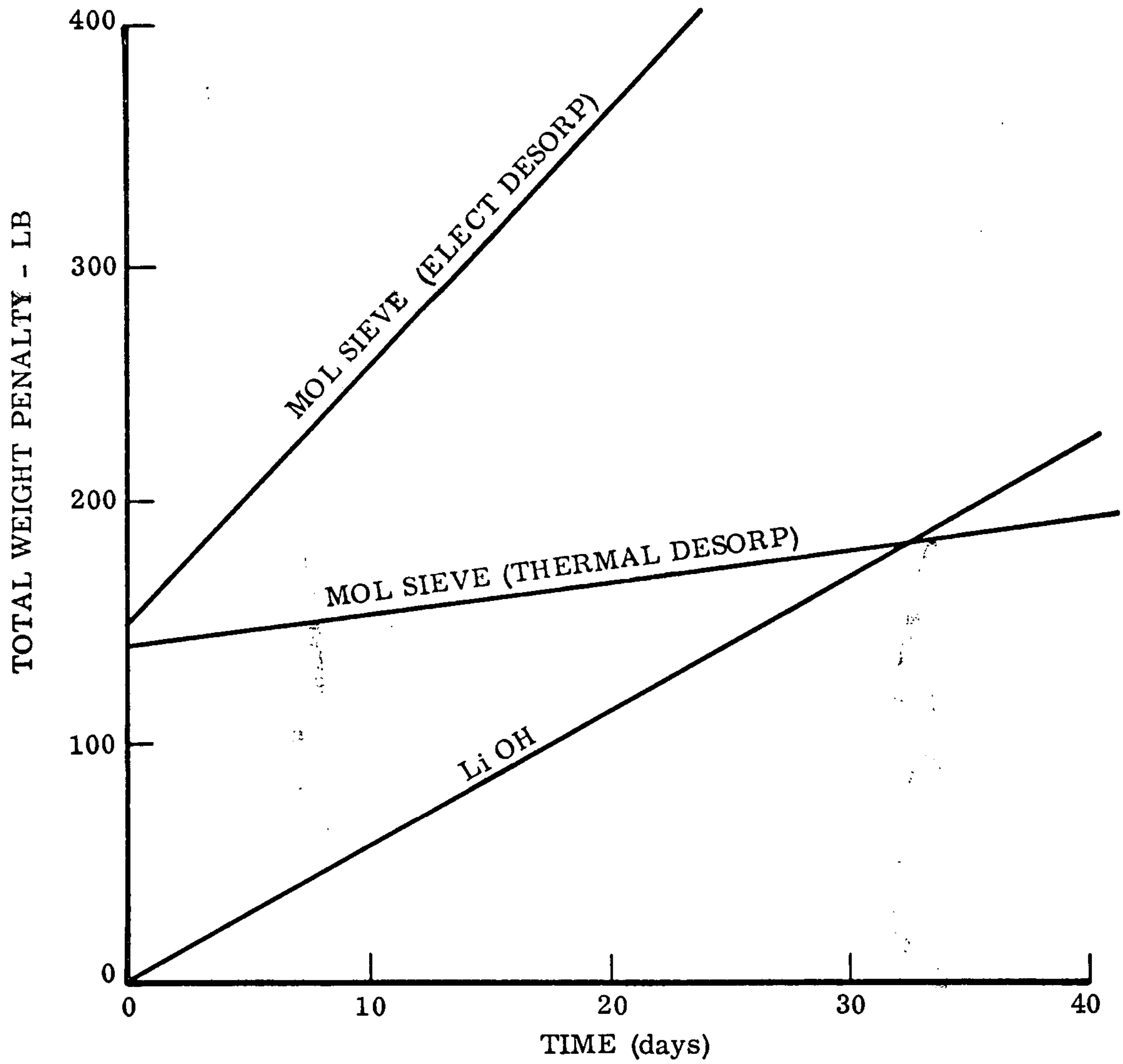


Figure 3-23. Weight Comparison of LiOH and Molecular Sieves

The weight and volume requirements for the shuttle concepts are summarized in Table 3-31. Supercritical storage was selected for use over subcritical storage because of its past successful use and development status. It was selected for Concepts A, B, and C over high pressure storage because of its lower weight. For the smaller quantities of gas required for the Concept D habitability kit high pressure storage was used. In this case the tankage weight savings were not judged to be enough to outweigh the advantages of simplicity, low cost, long shelf life and reliability of high pressure storage.

Table 3-31. O_2 and N_2 Weight and Volume

Concept/Module	A		B		B & C				D	
	Support Module (5-day)		Support Module (30-day)		Shuttle for B & C (25-day)		Support Module (30-day)		Habitability Kit (5-day)	
Requirement	O_2	N_2	O_2	N_2	O_2	N_2	O_2	N_2	O_2	N_2
<u>Fluid Weight (lb)</u>										
1. Breathing O_2	19	0	112	0	93	0	112	0	19	0
2. Module Pressurization	144	486	0	0	0	0	56	189	0	0
3. Emergency Repress.	0	0	75	253	23	75	75	253	0	0
4. Leakage Make-up	5	15	28	92	23	77	28	92	5	15
5. Reserve	34	100	43	69	28	31	55	107	5	3
TOTALS	202	601	258	414	167	183	326	641	29	18
<u>Tankage</u>										
1. Type	← Supercritical →								Hi Press.	
2. Weight (dry-lb)	61	181	78	124	50	55	98	193	68	45
3. Tank & Fluid Weight (lb)	263	782	336	538	217	238	424	834	97	63
4. Volume (ft^3)	3.7	15.7	4.7	10.8	3.0	4.8	5.9	16.7	1.0	1.0

3.9.2.3 Water and Waste Management. For all concepts, water is available from the fuel cells in excess of that required for crew drinking, food reconstitution, and personal hygiene. This water is relatively pure and requires only minor filtering to be potable.

A typical waste management system concept applicable to the support module employs air flow to assist the zero-g collection of urine and feces. The air returns to the cabin through a replacable activated charcoal filter for odor control. Feces and other solid wastes are collected, dried, and stored in a single container.

3.9.2.4 Personal Hygiene. The mission duration influences the nature and extent of personal hygiene activities. Table 3-32 lists these activities for the 5- and 30-day cases.

Table 3-32. Personal Hygiene Activities and Wastes

Item	Mission Duration	
	5 Days Concepts A & D	30 Days Concepts B & C
Hair cutting	No	No
Shaving	Yes	Yes
Hand and face cleansing	Yes	Yes
Whole body bathing	Yes	Yes
Nail clipping	No	Yes
Tooth brushing	Yes	Yes
Clothing changes	Yes	Yes
Wastes	Shaver clippings Used wash water Nail clippings Soiled clothing	Shaver clippings Used wash water Nail clippings Soiled clothing

Referring to this table, hair cutting is not a requirement for durations up to 30 days if the head is shaved or clipped very close just before the start of the mission. If hair growth causes discomfort while wearing a helmet, the head can be periodically shaved with the same mechanical shaver that is provided for the face. Shaving the face can also be optional for longer missions and omitted in short ones. Personal hygiene water is provided for all concepts, and the quantity is sufficient for whole body bathing by sponge techniques. A shower is not considered favorable because it would require more water and more pressurized volume within the crew module. When tooth brushing is done, the use of an ingestible cleanser will preclude waste handling. For the 30-day mission, about one outer clothing change per week is provided.

3.9.3 SUPPORT MODULE EC/LS DESIGN. The weight, volume, and power of the EC/LS subsystems aboard the support modules are summarized in Table 3-33 for each of the operational concepts (A, B, C and D), and for each of the major subsystems within the EC/LS. In general, the fixed EC/LS components aboard the support module for Concepts A, B, and C, and in the crew habitability kit for Concept D, are all about the same. In some cases the size is variable as in the case of a food storage cabinet for 5 days versus one for 30 days.

The major difference between the concepts is in the quantity of consumables aboard. The quantity aboard Concept D is the least. The quantity of O_2/N_2 is low because there are no requirements for module pressurization, and requirements for breathing and leakage makeup are low for the relatively short mission. Other consumables such as food and LiOH are also low due to the short mission. The consumables for Concept A are identical to Concept D except for the added pressurization gas. Enough O_2/N_2 was provided for three pressurizations of CM-1 experiment modules. Concept B and C both require more consumables because of the 30-day mission. Concept C requires more O_2/N_2 than B in order to pressurize the dormant experiment module.

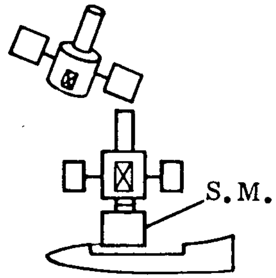
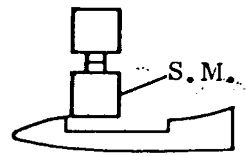
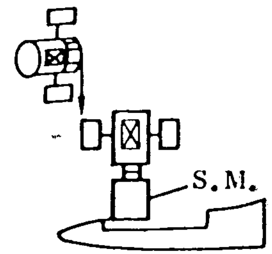
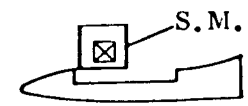
A typical support module EC/LS concept is shown in Figure 3-23. Supercritical O_2 storage is combined for both the fuel cells and EC/LS. Fuel cell water is purified for EC/LS use in waste management, food reconstitution, drinking, and personal hygiene. Currently, it has been assumed that waste water vapor can be vented overboard on a scheduled noninterference-with-experiments basis. Two water tanks are provided to allow for cyclic use and testing of purified water to certify its potable quality. An air loop is provided for pressure suit operation as well as cabin air dehumidification, CO_2 removal, and contaminant removal. Silica gel canisters provide backup cabin dehumidification in case of condenser/separator failure. In this case, suit loop air cooling would be accomplished with a backup air cooler.

3.9.4 SHUTTLE EC/LS CONSUMABLES. As discussed in Section 3.9.1, EC/LS consumables for the two shuttle crew men in excess of five days must be deducted from the payload. The weight of these consumables is shown in Table 3-34. O_2/N_2 is included for breathing, leakage makeup, and an emergency re-pressurization. Lithium hydroxide and charcoal are added for air purification, and food is required for the added 25-day stay time.

3.9.5 SUPPORT MODULE EC/LS CHANGES TO ACCOMMODATE TWO ADDITIONAL CREWMEN. Some of the FPEs being carried in Concept C require up to four men; e.g., biomedical experiments. The changes that result in the support module to accommodate the two extra men are noted below.

The basic EC/LS equipment for the support module has been shown in Figure 3-24 and Table 3-33. The type of equipment will be the same for the four-man crew, but its amount and size will increase. The weight and power required for this case and a

Table 3-33. EC/LS Subsystem Properties of the Support Module

Operation Concept →	A			B			C			D		
Support Module EC/LS Properties ↓				 EARTH			 ON-ORBIT OR EARTH			 EARTH		
Requirements:										Kit		
Crew	2 men			2 men			2 men			2 men		
Mission duration	5 days			30 days			30 days			5 days		
Exp. module Pressurization required	Yes			No			Yes			No		
Subsystem Weight, Volume & Power:	lb	ft^3	watts	lb	ft^3	watts	lb	ft^3	watts	lb	ft^3	watts
O_2/N_2 storage (super.)	1,045	19.4	150	874	15.5	30	1,258	22.6	35	160	2.0	0
Atm. purif. (LiOH)	83	3.5	20	265	11.0	70	265	11.0	70	73	3.1	10
Envir. control	107	5.4	175	107	5.4	175	107	5.4	175	70	2.8	125
Life support	155	8.5	55	396	17.5	95	396	17.5	95	155	8.5	55
Crew equipment	401	39.0	200	668	46.0	200	668	46.0	200	401	39.0	0
Total	1,791	75.8	600	2,310	95.4	570	2,694	102.5	575	859	55.4	190

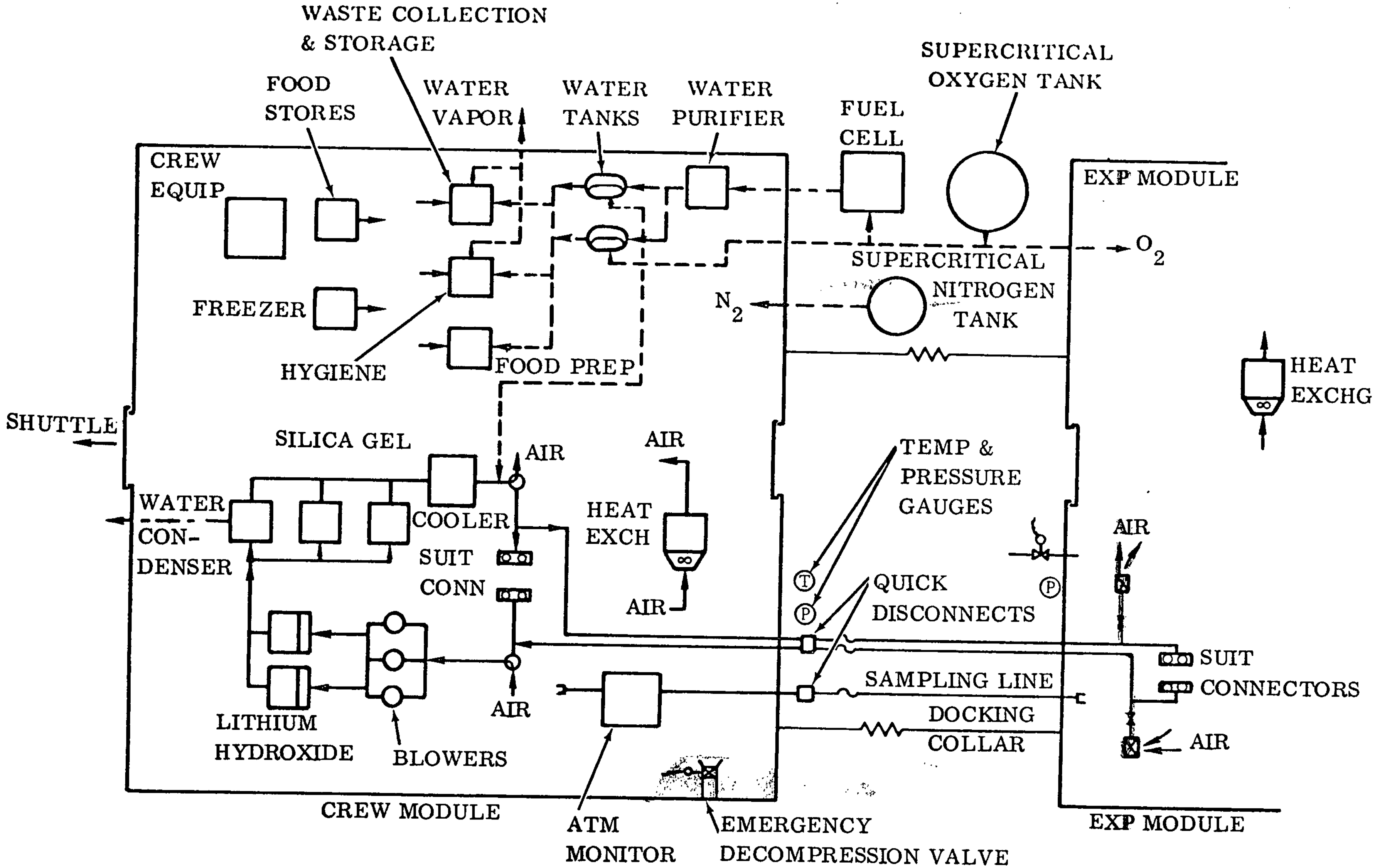
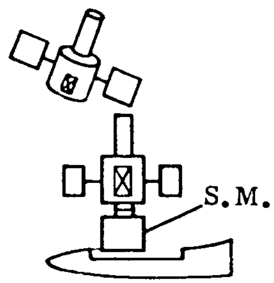
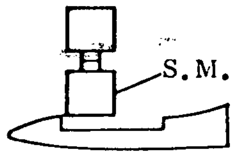
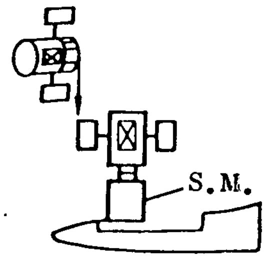
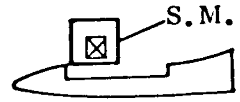


Figure 3-24. Support Module EC/LS Schematic

Table 3-34. Effect of Experiment Module Operation on Shuttle EC/LS Subsystem Consumables

Shuttle EC/LS Properties	OPERATIONAL CONCEPTS			
	A	B	C	D
		 EARTH	 ON-ORBIT OR EARTH	 EARTH
Basic Requirements				
Crew	2 Men	2 Men	2 Men	2 Men
Δ Stay time	0	25 Days	25 Days	0
EC/LS Subsystem Weight				
O_2/N_2 (super.)	0	460 lb	460 lb	0
Atm. purif. (LiOH)	↓	156 lb	156 lb	↓
Envir. control		0	0	
Life support		225 lb	225 lb	
Crew equipment		246 lb	246 lb	
Total	0	1087 lb	1087 lb	0

comparison to the two-man system are:

	4 Men		2 Men		Δ	
	lb	watts	lb	watts	lb	watts
1. Atmospheric storage	1433	35	1258	35	175	0
2. Atmospheric control	445	70	265	70	180	0
3. Environmental Control	162	275	107	175	55	100
4. Food & water	585	135	330	85	255	50
5. Waste & hygiene	95	15	66	10	29	5
6. Crew Equipment	1174	250	668	200	506	50
Total	3894	780	2694	575	1200	205

The atmospheric storage vessels must be slightly larger to accommodate the added breathing oxygen. The atmospheric control equipment includes LiOH for CO_2 removal, which must be doubled. Environmental control equipment includes silica gel canisters for emergency dehumidification. The size of these canisters must also be doubled. Twice as much food is required, and the crew equipment must be increased to include pressure suits, garments, and storage compartments.

3.10 MAINTAINABILITY/RELIABILITY ANALYSIS

The objective of this analysis was to develop design guidelines for experiment modules which will minimize the cost of sustaining experiment operations. The costs of providing the high degree of module reliability needed for long life were traded off with the alternative cost of achieving long life through repair. The goal was to define the level of experiment and supporting subsystem reliability with the associated repair that results in the lowest program cost consistent with experiment missions and crew limitations. This lowest cost combination of subsystem reliability and maintenance was determined in accordance with the following key factors as shown in Figure 3-25.

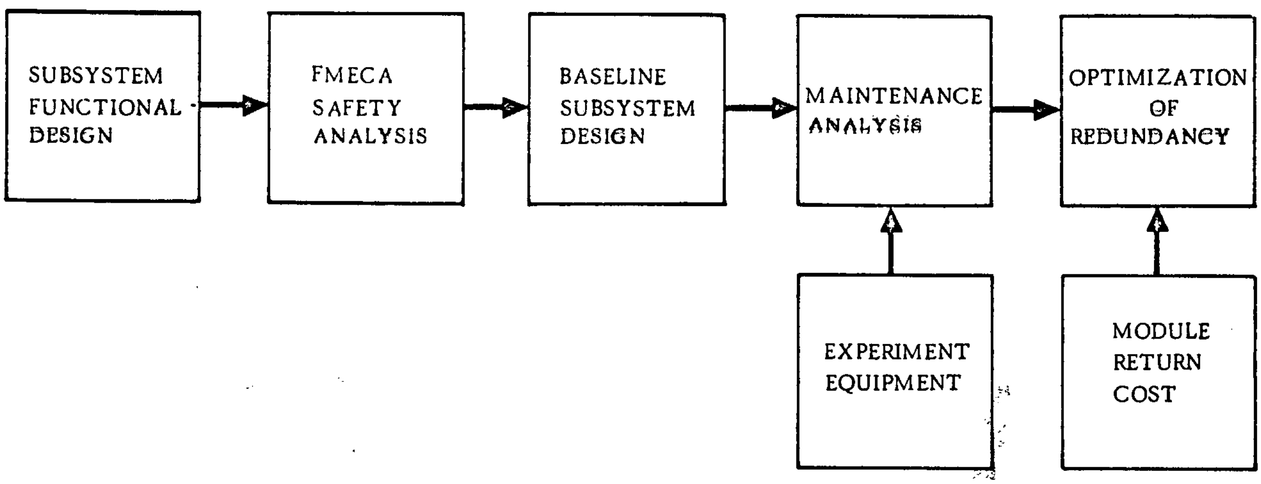


Figure 3-25. Module Maintainability Approach — Free-Flying Astronomy Module

Experiment equipment and supporting subsystems include redundancy of critical components to provide a high probability of module recovery. An additional consideration is to what degree will the expected failures over a given period of time place demands on the crew and logistics system to accomplish repair. Failures can be reduced by increasing redundancy in the experiment and supporting subsystems prior to launch. The cost of increasing redundancy was compared to the cost of repair. The output of the analysis provides the following information:

a. Redundancy needed to satisfy fail-operational/fail-safe requirements in accordance with the failure modes, effects, and criticality analysis (FMECA).

b. Cost, weight, and volume increments required for the shuttle-only case over the baseline space station case.

3.10.1 SAFETY AND FMECA — GROUND RULES AND RESULTS. The FMECA conducted on each subsystem used the space station ground rules as the governing criteria in providing backup capability for critical functions. Critical functions for the experiment modules were established as being those connected with safe flight and control of free-flying modules. Functions connected only with continued conduct of experiments were classified as noncritical. The increase in subsystem cost and weight to provide this safe-flight capability as compared to a purely functional system for the six free-flying modules is shown below.

Net effect on module subsystems weight	+ 674 lb	8.8%
Subsystems volume	+ 51 ft^3	13.4%
Subsystem unit cost	+ \$3.9M	19.9%
CM-1 module total cost (six modules)	+ \$23.4M	19.9%

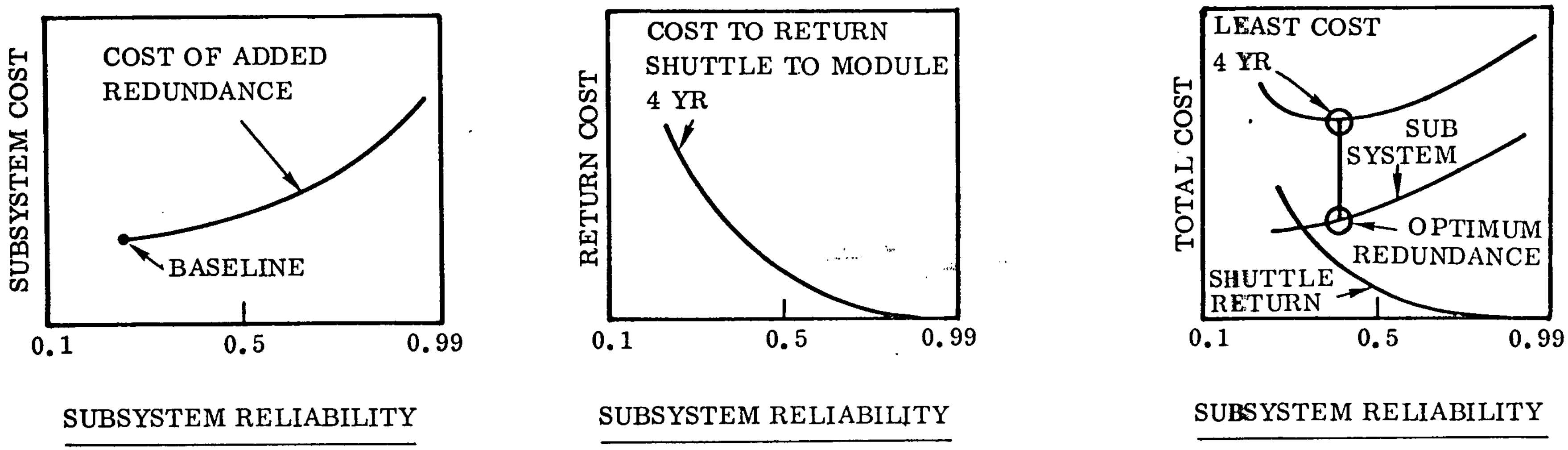
The majority of the increase was in RCS, stability and control, EC/LS, G&N, and communication and data management subsystems.

3.10.2 OPTIMIZATION OF SUBSYSTEMS FOR MAINTAINABILITY. Module subsystems designed to meet safety requirements have very high reliability for the controlled flight portion of their total operation. With this high reliability of module recovery for repair at the shuttle, the only significant parameter is the expected number of failures — failures that result in the need for a shuttle launch to effect repair of the module.

These repair trips can be reduced by further increasing redundancy in the subsystems. The cost of increasing redundancy can be compared to the cost of the alternate option, returning the shuttle for module repair. Addition of these two costs, subsystem redundancy and shuttle return costs, will indicate the optimum increase in subsystem redundancy, Figure 3-26.

A similar optimization of subsystem redundancy for the space base for four year operation was constructed for comparison purposes. Assumptions are noted on Figure 3-27.

3.10.3 OPTIMIZATION OF SUBSYSTEM REDUNDANCY (SHUTTLE-ONLY). Figure 3-28 shows the results of optimization analysis. Cost of shuttle returns for repairs for a 4-year period is plotted as a function of the number of expected failures per year.



SUBSYSTEM COST +

BASELINE BY FMECA
ADD REDUNDANT
COMPONENTS ON
GREATEST $\Delta R/\Delta \$$
RATIO

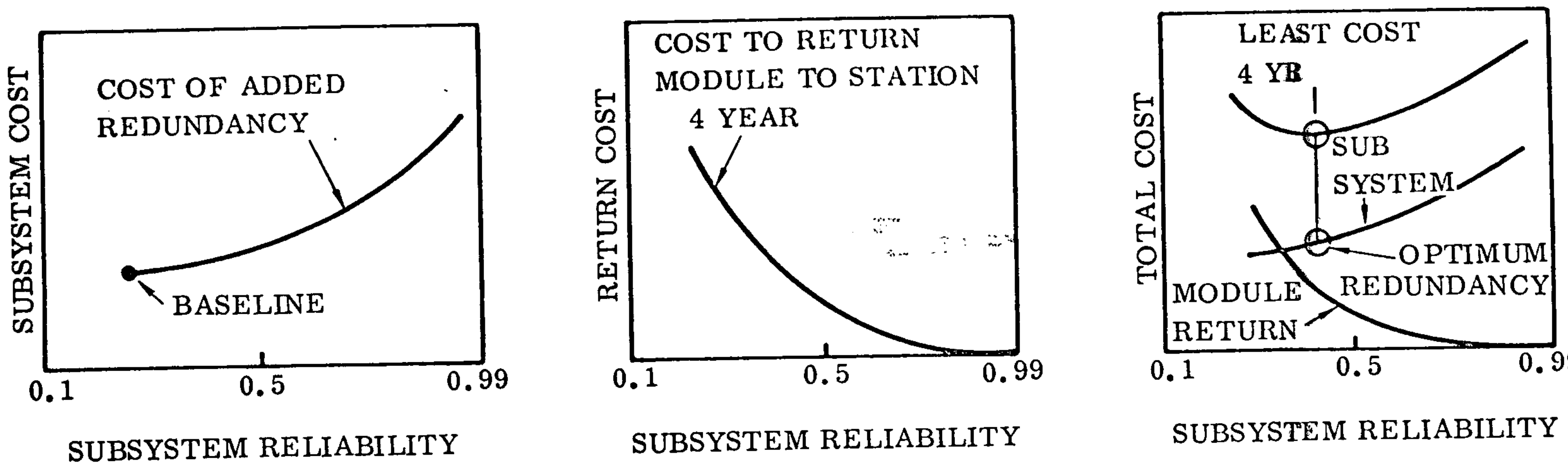
SHUTTLE RETURN COSTS =

PER RETURN CYCLE:		
PROPELLANTS (MODULE)		
80 LB AT 250 $/LB	=	20K
CREW HR		
14 HR AT 1K $/HR	=	14K
EXPERIMENT LOST TIME		
66 HR AT 1.5K $/HR	=	99K
SHUTTLE OPERATIONS COST	=	4100K
TOTAL	=	4233K

TOTAL COSTS

SUBSYSTEM VS. RELIABILITY
PLUS
SHUTTLE RETURN VS. RELIABILITY
EQUALS
TOTAL COST
LEAST TOTAL COST POINT
DETERMINES OPTIMUM
SUBSYSTEM RELIABILITY

Figure 3-26. Optimization of Subsystems for Maintainability — Shuttle-Only



SUBSYSTEM COST +

BASELINE BY FMECA
ADD REDUNDANT COMPONENTS ON GREATEST $\Delta R/\Delta \$$ RATIO

MODULE RETURN COSTS =

PER RETURN CYCLE:

PROPELLANTS		
240 LB AT 250 $/LB	=	$60K
CREW HR		
8 HR AT 1K $/HR	=	8K
EXPERIMENT LOST TIME		
22 HR AT 1.5K $/HR	=	33K
TOTAL	=	101K

TOTAL COSTS

SUBSYSTEM VS. RELIABILITY
PLUS
MODULE RETURN VS. RELIABILITY
EQUALS
TOTAL COST
LEAST TOTAL COST POINT DETERMINES OPTIMUM SUBSYSTEM RELIABILITY

Figure 3-27. Optimization of Subsystems for Maintainability — Space Station

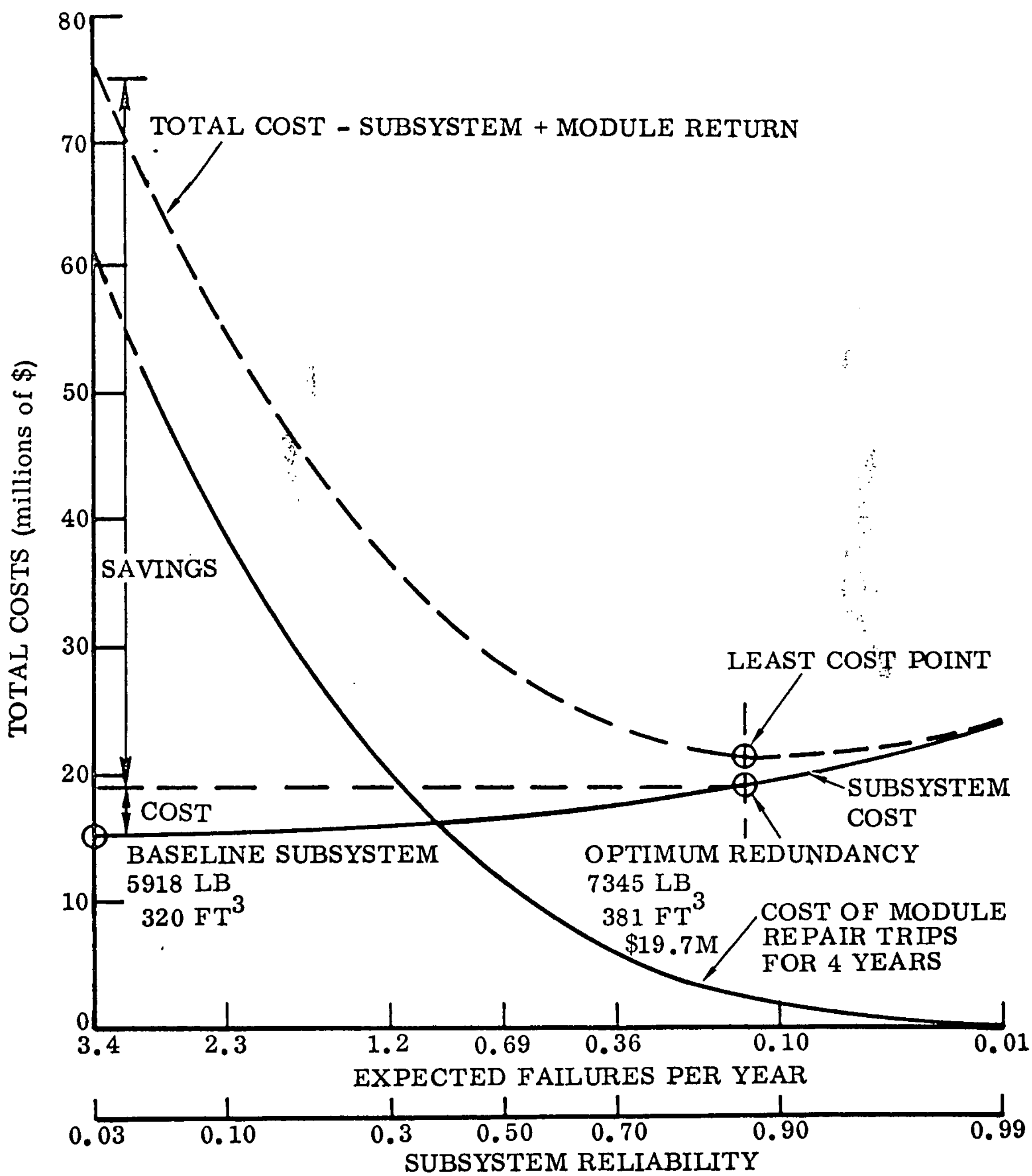


Figure 3-28. Optimization of All Module Subsystems for Redundancy — Shuttle-Only

Module subsystem cost is plotted as a function of the added cost of redundancy to achieve a decrease in the number of failures per year.

The total of these two costs shows a least-total-cost point and related expected failures per year. The indicated increase in subsystems cost will provide a four-year savings as shown in module return cost.

3.10.4 OPTIMIZATION OF SUBSYSTEM REDUNDANCY (SPACE STATION BASELINE). Figure 3-29 shows the results of the optimization analysis for the space station baseline for a four-year period. Cost of module returns for repairs for a four-year period is plotted as a function of the number of expected failures per year. Figure 3-29 was constructed for a four-year period to compare the optimum redundancy and least cost points of the space station operation to that of the shuttle-only case. Figure 3-30 shows the comparison of optimum cost points for redundancy, space station versus shuttle-only.

3.10.5 MAINTAINABILITY ANALYSIS CONCLUSIONS. The conclusions reached as a result of analyzing module subsystem maintenance for the shuttle-only program versus the space station baseline are:

a. The current subsystem designs for both space station and shuttle-only maintenance are realistic — they reflect safety considerations and maintenance cost effectiveness.

b. The comparison of the least cost point for the shuttle-only versus space station operation indicates the following changes to the subsystems.

Cost	=	+ \$3.56M
Weight	=	+ 1198 lb
Volume	=	+ 54 ft^3

3.11 SAFETY CONSIDERATIONS

3.11.1 LAUNCH PHASE

a. Provisions are required for venting the LO_2 and LH_2 tanks outside of the shuttle fuselage at widely separated locations. This will necessitate an interface with the shuttle design.

b. A jettison capability of the module must be present in the shuttle to ensure a safe abort capability for the shuttle.

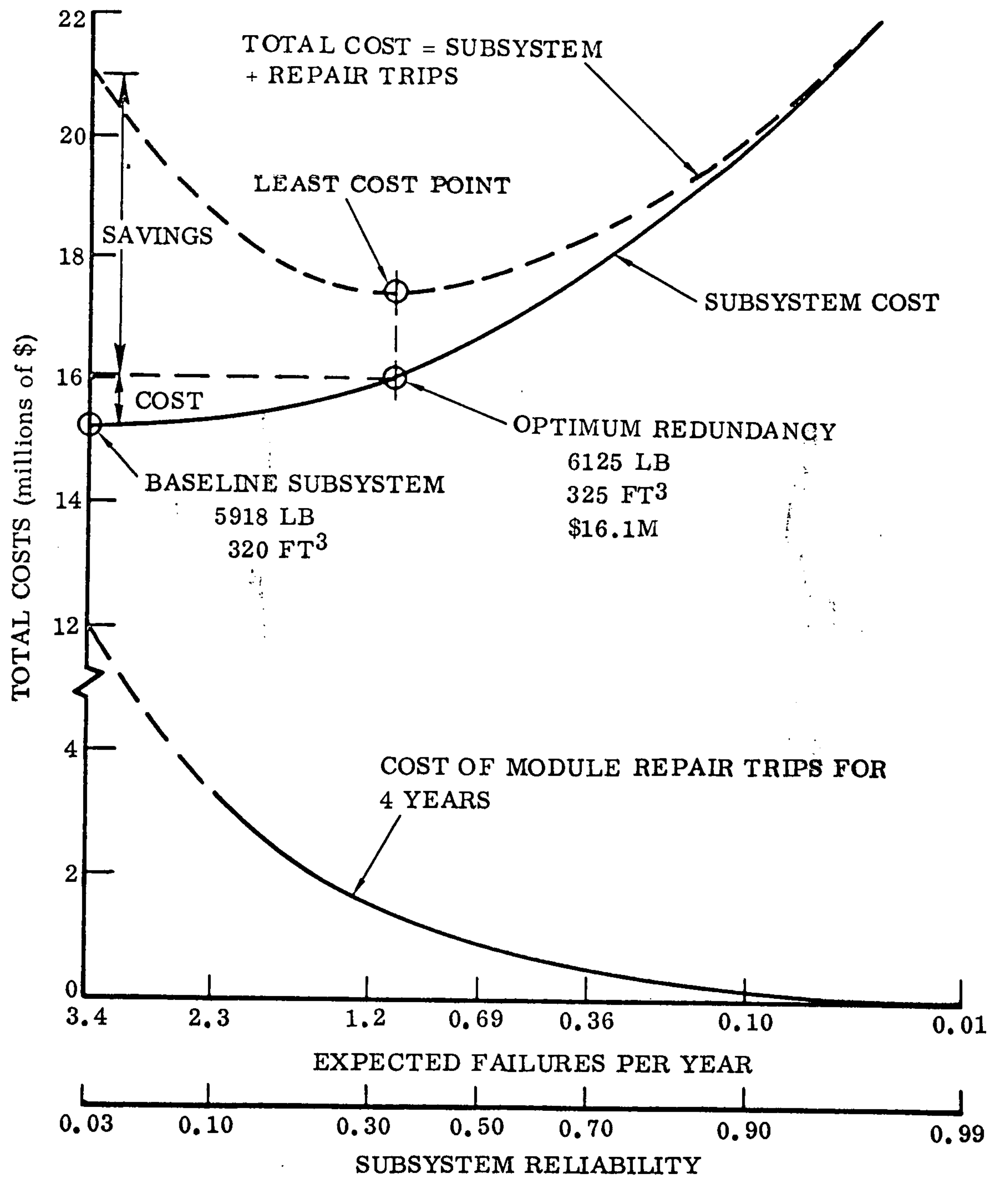


Figure 3-29. Optimization of All Module Subsystems for Redundancy — Space Station Baseline

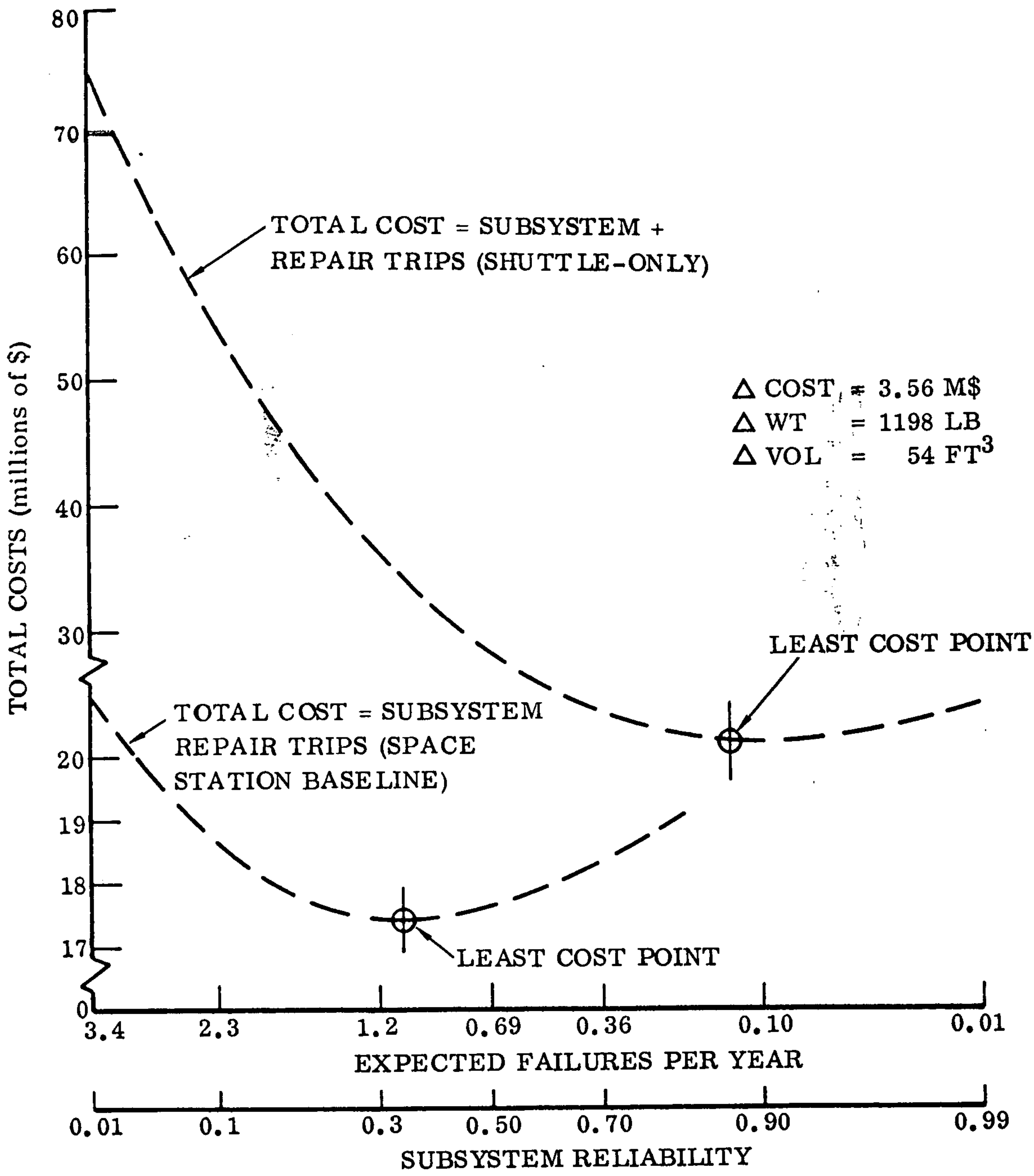


Figure 3-30. Comparison of Optimum Cost Point for Redundancy — Space Station vs. Shuttle-Only

3.11.2 ON-ORBIT PHASE

a. The temperature, pressure, and oxygen level of the support module must be determinable and controllable from within the shuttle to ensure a safe environment for crew entry.

b. The temperature, pressure, and oxygen level of the experiment module must be determinable and controllable from within the support module, particularly for the free-flying module, to ensure a safe environment for crew entry.

c. A communication link is required between the experiment module, the support module, and the shuttle. This may be radio (such as "hot" mikes in each area), TV monitors with sound, or any other suitable system.

d. The following operational safety procedures are recommended:

   1. One shuttle pilot must remain in the cockpit at all times, thus ensuring that a malfunction of the support or experiment module will not preclude safe return of the shuttle.

   2. Whenever it is necessary for both experiment crewmen to enter the experimental module, one shuttle pilot must be located in the support module. This is particularly critical if the pilots do not have direct shirtsleeve access from the cockpit to the support module. (See item e.)

e. A shirtsleeve access between the cockpit and the support module is essential from a crew safety point of view, as well as from an operational flexibility point of view. In the event of an emergency in one of the modules, the time delay to retract the modules (or for the crew to put on space suits) may be catastrophic. This would be further aggravated if a malfunction of the retraction mechanism should occur. Many other safety problems would also be precluded or corrected by this direct access. Solutions to this problem include: providing an environmentally airtight duct between the shuttle cargo bay access tunnel and the support module; or permanently locating the support module in the cargo bay flush with the shuttle tunnel and providing for movement of the experiment module, after rotation out of the cargo bay, over the support module.

f. Backup mechanisms are required to extend and retract the module system and any required solar panels or other equipment. In the event of malfunction of the backup system, a jettison system must be provided, such as explosive bolts, for each piece of equipment and the module system.

g. All equipment possible should be mounted such that it can be moved away from the outer walls of the modules in order to permit repair to any puncture of the inner skin. A set of self-adhesive patches, flat and saucer shaped, should be provided in the module.

h. All tools and materials to be used in the modules must be non-conductive (non-sparking) and non-flammable.

i. Provisions are required for safing of the modules (fuel cells and RCS) prior to retraction of the modules into the shuttle.

j. Provisions for dumping of remaining LO_2 and LH_2 prior to retraction of the modules into the shuttle are desirable, from both a safety and a weight consideration.

k. Potential hazards to the experiment crew have been identified as:

Crew in Experiment Module	Crew in Support Module	Corrective Action
Loss of pressurization	Loss of pressurization	Emergency O_2 and immediate exit to crew.
Loss of EC/LS	Loss of EC/LS	Emergency O_2 and immediate exit to module/shuttle.
Loss of electrical power	Loss of electrical power	Immediate exit to support module/shuttle.
Jamming of hatch to support module	Jamming of hatch to shuttle tunnel or to cockpit	For access from experiment and support modules, emergency opening (only) provisions are required. For access to cockpit, a resealable emergency opening system is required.
Fire or explosion	Fire or explosion	Provisions to jettison the experiment module (only) and the experiment and support modules (together) are required. Crew should have a hand extinguisher for small (probably electrical) fires.
Failure of solar panels or other extendable equipment to retract	Failure of modules retraction mechanism	Provisions to jettison the extended systems or the modules are required (see item f).
Loss of RCS or other control of free-flying experiment module during docking	—	Backup command capable of cutting off errant system and/or backup control system capable of returning experiment module to safe docking.

SECTION 4

PROGRAM COST AND SCHEDULE ESTIMATE

4.1 PROGRAM COST ESTIMATE

The preliminary program cost estimates for the shuttle-only program are summarized in this section for a program consisting of common modules CM-1, CM-3, CM-4; the support module; and the propulsion slice. These costs were arrived at by means of a refined version of the cost model and the methodology utilized during the mainline study task. The general ground rules used in generating these cost estimates are:

a. 1970 dollars are used.

b. No inflation or labor rate escalation is included.

c. No discounting is used.

d. No growth or contingency costs are included.

e. 10% contractor fee is included.

It should be noted that the costs shown in this volume are estimated on a somewhat different basis than those shown for the mainline study in Volume IV and caution should be used in any direct comparison. First, the shuttle-only concept program discussed in this volume provides for the full Blue Book experiment program rather than those for the mainline case where some experiment FPEs are incorporated integrally on the space station itself. Additional modules are therefore needed to accommodate these experiments. Secondly, design definition of the modules and the program evolved somewhat between the shuttle-only task and the final configurations reported in Volume IV. Lastly additional certain methodology changes were made in the manner that costs were calculated for DDT&E and unit cost, in the intervening period. The cost differences are relatively minor and should not exceed 10%, well within the overall confidence level for this Phase A estimate of about ±20%.

Further it must be noted that the costs shown for this shuttle-only case include all of the elements of the overall program with the exception of the development and investment for the space shuttle vehicle. (The mainline study cost also exclude cost for the space station and its associated flight operations.) These differences preclude a direct comparison of alternate experiment module programs without the appropriate qualifications.

This total program, summarized in Tables 4-1 through 4-3, consists of design, development, test, and evaluation (DDT&E) or nonrecurring cost, production cost for the flight articles (recurring production), and operations cost (recurring operations).

Table 4-1. Preliminary Shuttle-Only Experiment Module Program Cost Summary (30-Day Shuttle Capability)

No. of Modules	CM-1 7	P/S 1	CM-3 5	CM-4 5	SM-30 10	Total
	Millions of Dollars					
Module DDT&E	236.4	47.8	217.7	165.0	134.7	801.6
Module unit cost	(19.95)	(2.56)	(14.55)	(13.03)	(15.12)	—
Total module production	139.6	2.6	72.7	65.2	151.2	431.3
Experiments	506.0	—	285.6	550.7	—	1342.3
Experiment integration	140.1	—	74.4	141.7	—	356.2
Interface hardware	96.8	—	30.2	68.7	—	195.7
Launch operations (module)	2.5	*	1.7	1.6	*	5.8
Shuttle operations	304.0	*	268.0	280.0	*	852.0
Flight operations (module)	73.0	*	38.0	37.8	*	148.8
Project management & support**						32.8
Total	1498.4	50.4	988.3	1310.7	285.9	4163.5

* Included with appropriate CM program
** Project level cost element

In addition a project management and support function is included for overall support and management of all elements of the project.

These total program costs are provided for three cases where:

a. A 30-day shuttle orbital stay time is available.

b. A 5-day shuttle orbital stay time is available.

c. A restricted experiment program is assumed for the 5-day shuttle to eliminate an unreasonable number of shuttle servicing flights.

As was recognized early, the 5-day orbital stay time capability imposes excessive requirements on the program in terms of number of shuttle flights required for some of the FPEs. This is in turn reflected in the shuttle operations costs, as may be seen in Table 4-2. A restricted experiment program was defined that eliminated FPEs requiring an excessive number of flights, but limits the scientific return. The cost for this

Table 4-2. Preliminary Shuttle-Only Experiment Module Program Cost Summary (5-Day Shuttle Capability)

No. of Modules	CM-1 7	P/S 1	CM-3 5	CM-4 4	SM-5 21	Total
	Millions of Dollars					
Module DDT&E	236.4	47.8	217.7	165.0	106.5	773.4
Module unit cost	(19.95)	(2.56)	(14.55)	(13.03)	(12.09)	—
Total module production	139.7	2.6	72.3	52.1	253.9	520.6
Experiments	506.0	—	285.6	304.7	—	1096.3
Experiment integration	140.1	—	74.4	87.7	—	302.2
Interface hardware	96.8	—	30.2	49.5	—	176.5
Launch operations (module)	2.5	*	1.7	1.3	*	5.5
Shuttle operations	376.0	*	1244.0	600.0	*	2220.0
Flight operations (module)	812.0	*	51.3	34.0	*	897.3
Project management & support**						37.7
Total	2309.5	50.4	1977.2	1294.3	360.4	6029.5

* Included with appropriate CM program

** Project level cost element

program is shown in Table 4-3. A 30-day shuttle stay time capability alleviates the shuttle flight problem somewhat and provides close to full experiment capability. This program is summarized in Table 4-1.

4.1.1 NONRECURRING (DDT&E). The results of the preliminary cost estimates of the current experiment module configuration are presented in Table 4-4 for the three cases under study. These estimates are for CM-1, propulsion slice (P/S), CM-3, and CM-4 common modules and the 5-day and 30-day support module, respectively. These modules are assumed to be man-rated space flight hardware of minimum complexity commensurate with performance and reliability requirements. Maximum use is made of developed and qualified off-the-shelf components and assemblies that will be available in the experiment module time span. New hardware will be developed only when absolutely necessary, and wherever possible will be within the current state of the art. The module subsystems are maintainable in orbit and appropriate redundancy

Table 4-3. Preliminary Shuttle-Only Experiment Module Program Cost Summary (5-Day Shuttle Capability - Restricted FPE Program)

No. of Modules	CM-1 6	P/S 0	SM-3 1	CM-4 1	SM-5 4	Total
	Millions of Dollars					
Module DDT&E	236.4	—	217.7	165.0	106.5	725.6
Module unit cost	(19.95)	—	(14.55)	(13.03)	(12.09)	—
Total module production	119.7	—	14.6	13.0	48.4	195.7
Experiments	484.3	—	3.8	25.0	—	513.1
Experiment integration	133.5	—	1.0	6.6	—	141.1
Interface hardware	77.8	—	3.7	12.0	—	93.5
Launch operations (module)	2.1	*	0.3	0.3	*	2.7
Shuttle operations	208.0	*	40.0	100.0	*	348.0
Flight operations (module)	63.4	*	4.9	4.7	*	73.0
Project management & support**						17.5
Total	1325.2		286.0	326.6	154.9	2110.2

* Included with appropriate CM program
** Project level cost element

is incorporated to meet the reliability requirements. The common modules are assumed to be developed by a single contractor in an integrated concurrent program and full advantage is taken of common structure and subsystems between these modules. Development costs for these similar or identical subsystems are prorated equally between the three experiment modules. For these reasons, cost shown for the individual module programs are not necessarily applicable if taken out of context of an integrated program. For the support modules, development is expressed as a Δ cost to the CM-3 module.

The test hardware cost element consists of the major test hardware as well as major system test conductance. The major test article requirements were determined in the analysis of the test program discussed in Section 4.2. The test article quantity as well as the number of flight articles for the three cases is summarized in Table 4-5.

Table 4-4. Module Summary Costs (Millions of Dollars)

	CM-1		CM-3		CM-4		Propulsion Slice		5-Day Support Module		30-Day Support Module	
	DDT&E	Unit Cost	DDT&E	Unit Cost	DDT&E	Unit Cost	DDT&E	Unit Cost	DDT&E*	Unit Cost	DDT&E*	Unit Cost
Structure	8.33	1.71	8.33	1.71	13.50	2.07	8.50	0.82	3.70	1.90	6.47	2.17
Propulsion	—	—	—	—	—	—	14.10	1.01	—	—	—	—
RCS	3.77	1.47	3.77	1.15	3.77	1.47	—	—	—	—	—	—
EPS	5.67	2.48	8.67	2.34	3.67	1.10	—	—	11.00	1.46	14.20	2.93
EC/LS	7.66	2.04	20.76	3.07	7.56	2.59	—	—	16.50	2.50	20.50	2.98
Comm/Data	5.50	2.40	5.50	1.64	5.50	1.83	—	—	2.00	2.58	2.00	2.58
Stability & control	16.50	4.30	8.25	0.70	8.25	0.46	0.80	0.14	—	—	—	—
Guidance & navigation	2.00	0.13	2.00	0.08	2.00	0.13	—	—	2.00	0.51	2.00	0.51
FAICO	—	2.57	—	1.79	—	1.52	—	0.23	—	1.41	—	1.80
System test	82.12	—	67.38	—	50.27	—	3.95	—	15.55	—	19.45	—
GSE	21.87	—	20.32	—	14.15	—	6.42	—	17.07	—	21.40	—
Spares	12.83	—	8.97	—	7.59	—	0.16	—	7.05	—	9.00	—
Facilities	3.20	—	2.00	—	2.00	—	0.30	—	1.50	—	1.50	—
SE&I	33.25	—	30.79	—	23.25	—	6.79	—	14.97	—	19.00	—
Program management	12.16	1.03	11.20	0.75	8.49	0.67	2.46	0.13	5.48	0.62	6.93	0.78
Subtotal	214.87	18.13	197.95	13.23	150.00	11.84	43.47	2.33	96.83	10.99	122.45	13.75
Fee	21.48	1.81	19.79	1.32	15.00	1.18	4.35	0.23	9.68	1.10	12.24	1.37
Total	236.35	19.94	217.74	14.55	165.00	13.02	47.82	2.56	106.51	12.09	134.69	15.12

* Expressed as an increment to CM-3 DDT&E costs.

Table 4-5. Test and Flight Article Requirement

	CM-1	P/S	CM-3	CM-4	Support Module
Structural*	1	1	-	1	-
Engineering model	2	1	3	3	-
Flight module (30-day)	7	1	5	5	10
Flight module (5-day)	7	1	5	4	21
Flight module (5-day restricted)	6	0	1	1	4

* Structural article cost included in subsystem cost

Tooling is included in the subsystem development cost, and is not estimated separately. Cost for both the GSE development and GSE unit production is included in the module DDT&E cost. GSE development is estimated as a percentage of the subsystems and structure development, and GSE production units is estimated as a percentage of the subsystem and structure first unit cost. Two sets of operational GSE are included for CM-1, one for the propulsion slice, one for CM-3, one for CM-4, one for P/S, and three for the support module. Initial spares, included in DDT&E, are estimated as a fixed percentage per flight article of the subsystems unit cost. Consumption spares cost is included in the recurring-operations category.

Only nominal facility requirements are included in the DDT&E estimate. This cost covers clean rooms, RCS and propulsion test stands, stability and control test stand, and docking simulation. It is assumed that a large thermal vacuum space environment facility will be available without the necessity of acquiring a new one. Launch site vehicle receiving and checkout facilities are also assumed available.

Systems support (systems engineering and integration) and program management are estimated as fixed percentages of module DDT&E.

4.1.2 RECURRING PRODUCTION. Production unit cost for the subsystems was determined by use of subsystem cost estimating relationships (CERs) or in some cases component level estimates. Sustaining engineering is contained in these CERs and is not estimated separately. Final assembly installations and checkout (FAICO) is determined by a fixed percentage of the subsystem unit cost excluding structure.

Subsystem component modularity, in which unneeded components or capability may be avoided for individual modules, is used in determining these costs. For instance, in the case of solar arrays the number of panels may be tailored to the individual FPE electrical power requirement. Total production cost is obtained by summing the unit cost over the number of modules. No learning was assumed because of the small number of modules and the individual nature of each vehicle because of subsystem component modularity. Production management is estimated as a fixed percentage of the unit cost.

DDT&E and production costs contain all labor, materials, subcontracts, overheads, burdens, and G&A overrides.

4.1.3 EXPERIMENTS. Experiment hardware cost is based on data supplied by NASA. Experiment costs are assumed to include experiment DDT&E, prototype and test hardware, flight hardware, initial and consumption spares, GSE, and fee. No additional costs are included for experiment consumption spares or experiment update during the mission.

4.1.4 EXPERIMENT INTEGRATION. This category also includes the installation and checkout of the flight experiment in the flight common module. The experiment integration considered here is software associated with interface control (mechanical, thermal, dynamic, electronic, operational, sequencing, etc.) and with control of interactions between experiments. It does not include hardware since these items are accounted for in the interface hardware category. An allowance of 20% of the experiment cost with an additional 2% per experiment for multiple experiments is used for this cost element.

4.1.5 INTERFACE HARDWARE. Experiment interface hardware is defined as those additional items of equipment or hardware necessary for the experiment (as defined in the Blue Book) to operate when installed in the appropriate common module. Examples of this hardware include experiment mechanical mounting provisions or mounting bulkheads, telescope shrouds, experiment sequencers, experiment deployment arms, and fluid servicing equipment.

4.1.5.1 Recurring-Operational Cost. The operations costs include launch operations, shuttle operations, and flight operations. The experiment modules are based on five years of mission life for the astronomy modules and two years for all others. Module refurbishment and experiment replacement costs at the end of these experiment mission lives are excluded. The operational costs, however, are only for the period from the first launch to the point in time where it is assumed the space station is available (year N).

Cost estimates for operational experiment data reduction and analysis are excluded as being beyond the scope of the present study.

The module launch operations cost element includes module transportation to the launch site, launch site operations and support, and facilities and AGE maintenance.

The shuttle operations include all shuttle costs chargeable to transportation of the modules into orbit. It does not include development or investment costs for the shuttle. The launch vehicle considered for the experiment module and the servicing and logistic flights is a shuttle with an orbital payload capability of 25,000 pounds to a 270 n.mi/ 55 deg inclination orbit. A baseline launch operations cost of $4.0M was provided by MSFC for this vehicle. All flights were charged for the full launch cost and were not prorated by weight even though they may not have used the full weight and/or volume capability of the vehicle.

4.1.5.2 Flight Operations. This cost category includes consumption spares, training, support module refurbishment, and mission operations, control and planning. No cost is included for flight crew pay and allowances and ground tracking system operation.

Consumption spares are derived from the detailed results of Convair's reliability model used for the mainline study. This model provides expected value weight of the spares requirements over the given life of each subsystem. Average cost per unit of average weight is then used to determine spares cost estimates.

Because on-the-job training on engineering or flight vehicles is proposed, no costs were included for flight crew pay and allowances for training, nor are major training articles required. A nominal allowance was included, however, for each common module for general module familiarization courses and maintenance training.

Because of the large number of flights for each of the support modules, periodic refurbishment and overhaul will be required. A factor of 4.8% of unit cost once every 20 flights was used to establish this cost.

Costs for the overall ground mission control and operations and mission planning were not estimated in detail but a nominal allowance of $20M per year was included to cover these operations and tasks.

4.1.5.3 Phased Funding Requirements. The phased funding requirements for the individual common modules used with a 30-day shuttle are presented in Figure 4-1. The funding requirements accumulated for the three common modules, the propulsion slice, and the support modules are shown. A funding schedule in tabular form is presented in Table 4-6 for the module portion of the program.

The funding spreads are based on the schedules presented in Section 4.2 and are keyed to the fiscal year of the space station availability (FY-N). Appropriate spread functions were applied to individual cost elements or groups of cost elements over the activity time period and proper start date.

Table 4-6. Experiment Module Concepts Study Funding Spread (Millions of Dollars)

Years	N-11	N-10	N-9	N-8	N-7	N-6	N-5	N-4	N-3	N-2	N-1	N *	Total Cost
Common Module No. 1		7.3	34.4	64.7	115.3	159.7	169.5	279.6	252.2	246.6	169.1		1,498.4
Common Module No. 3		22.0	69.2	118.8	136.5	137.4	117.8	123.4	110.1	76.5	76.5		988.3
Common Module No. 4	2.0	25.8	80.4	150.0	207.7	239.7	166.3	164.5	115.5	79.5	79.5		1,310.7
Propulsion Slice		5.7	11.9	16.2	8.5	4.5	1.5	2.1					50.4
Support Module - 30 Day		16.0	33.7	45.6	24.0	21.8	96.4	48.4					285.9

* Space Station Available

NOTE:

The cost summaries in Tables 4-1 through 4-3 (GDC-XM-TN-200) are for an integrated program. Development costs for identical or similar subsystems are prorated over the appropriate modules. The development costs shown are not applicable if that module is developed by itself. Similarly, the support module development cost is an incremental cost in addition to the CM-3.

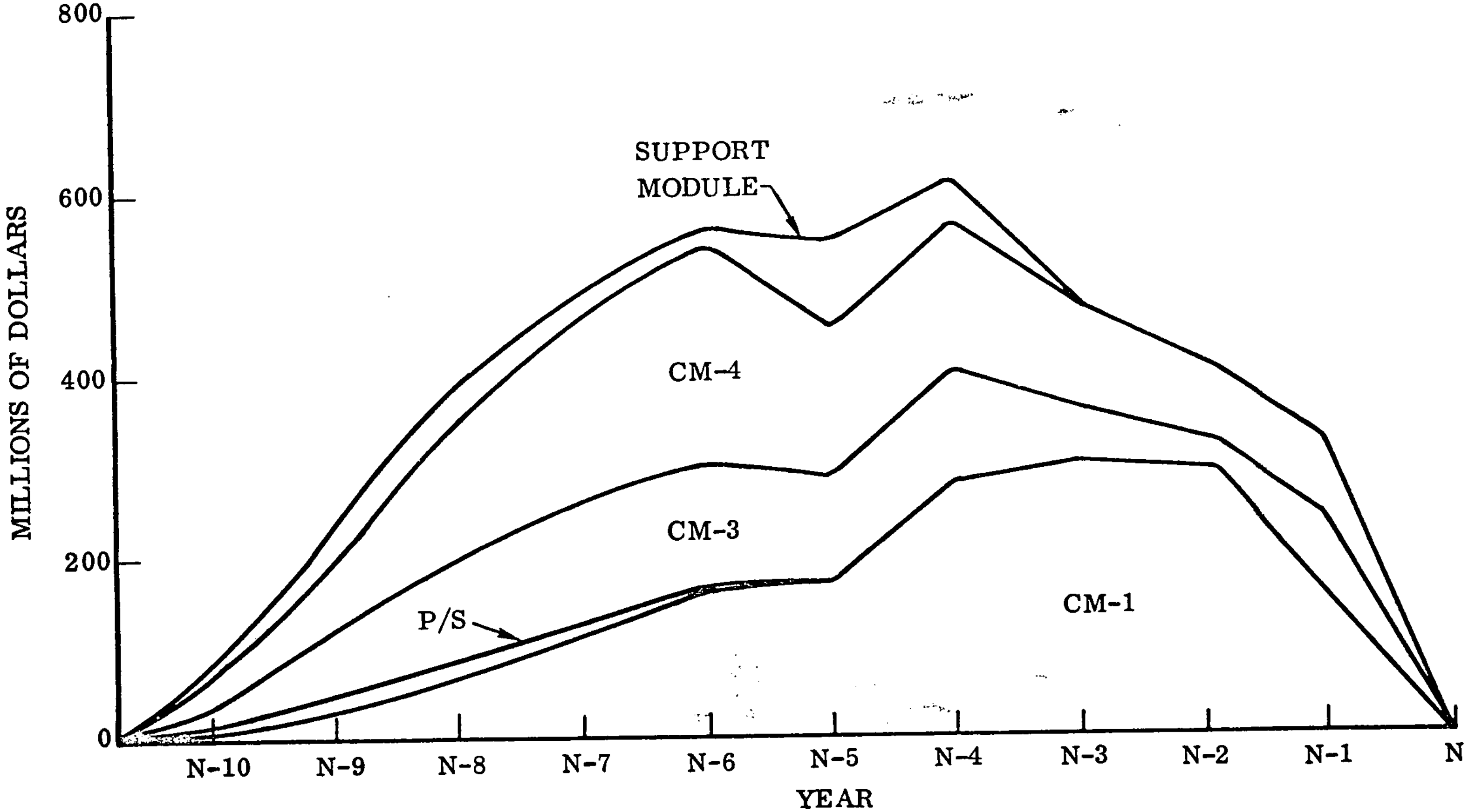


Figure 4-1. Phased Funding for 30-Day On-Orbit Capability Shuttle Case

4.2 DEVELOPMENT PLAN AND SCHEDULE

The experiment module program development and scheduling are constrained by the launch schedule derived from that provided by NASA, MSFC. This experiment module launch schedule is shown in Figure 4-2. All times are referenced to the space station availability in year N. A number of module launches are advanced or delayed in this schedule by three months in order to minimize the production tooling and/or optimize the use of engineering modules for experiment compatibility and verification. The modules showing a horizontal line ending with a caret have revised launch schedules. The open carets for Fluid Physics III and IV are launch dates of experiments only.

Figures 4-3 through 4-7 are the module production and testing schedules by module types. Because of the similarity of the module structures on the CM-1, CM-3, and crew modules, only one structural/thermal test vehicle has been assumed for the CM-1, CM-3, and crew module configurations. Similarly, at least one engineering model will be used for both CM-1 and CM-3 compatibility and verification testing.

The basic modules and subsystems go through an extensive environmental test program using worst case simulated experiment configurations. The experiments and experiment unique equipment will also be separately tested to the mission environment thereby reducing the tests of the module/experiment configuration during the compatibility phase.

Although not shown in the schedules, the engineering model of each experiment configuration will be used for shipping and pre-launch checkout proofing, astronaut training, and flight backup following verification testing. After launch of a flight module, the engineering model (flight backup) will normally be returned to the factory for rework to another experiment configuration.

As shown in Figure 4-7, the support module needs only one engineering model because of the similarity of vehicles.

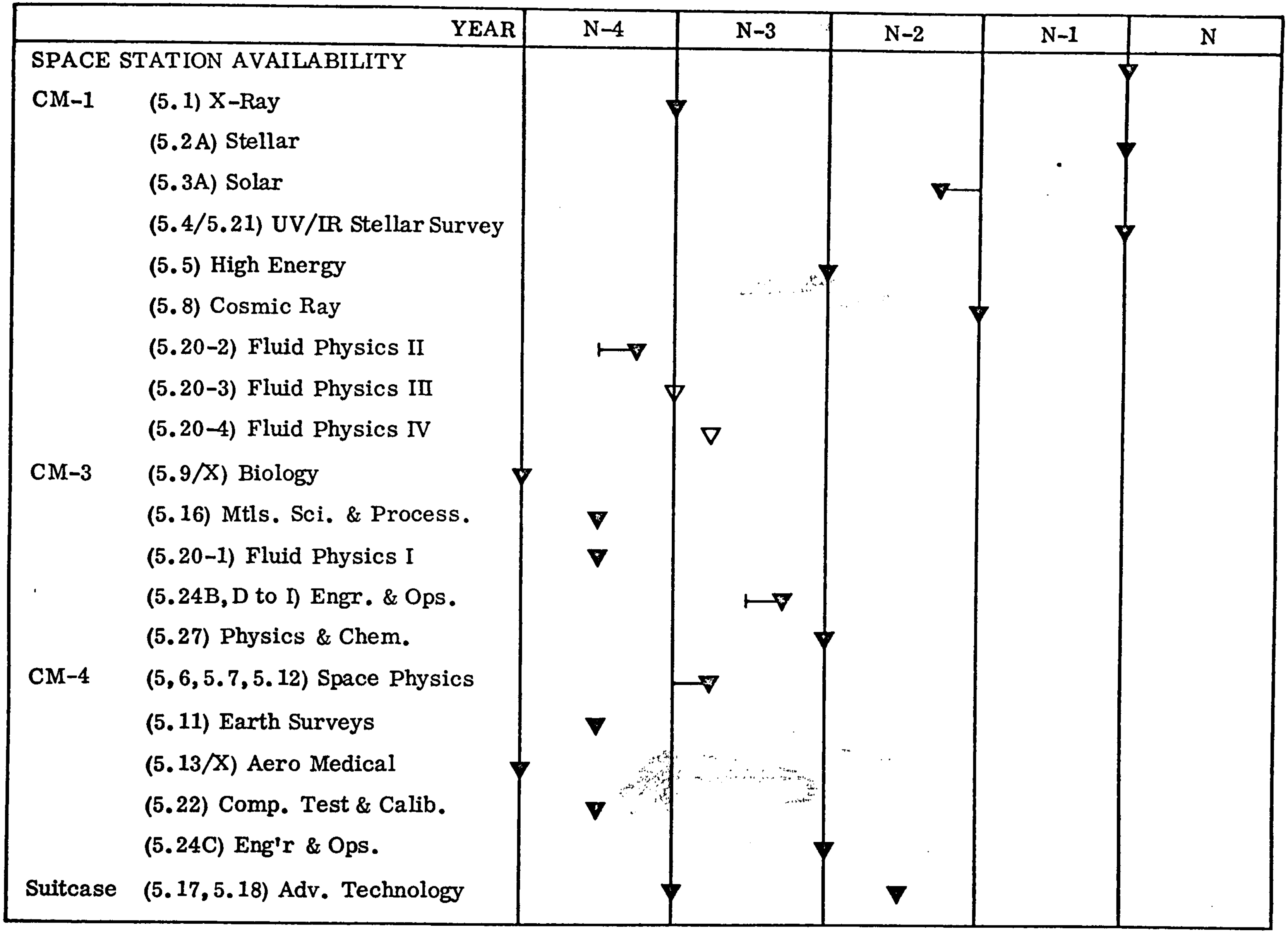


Figure 4-2. Shuttle Only Experiment Module Launch Schedule

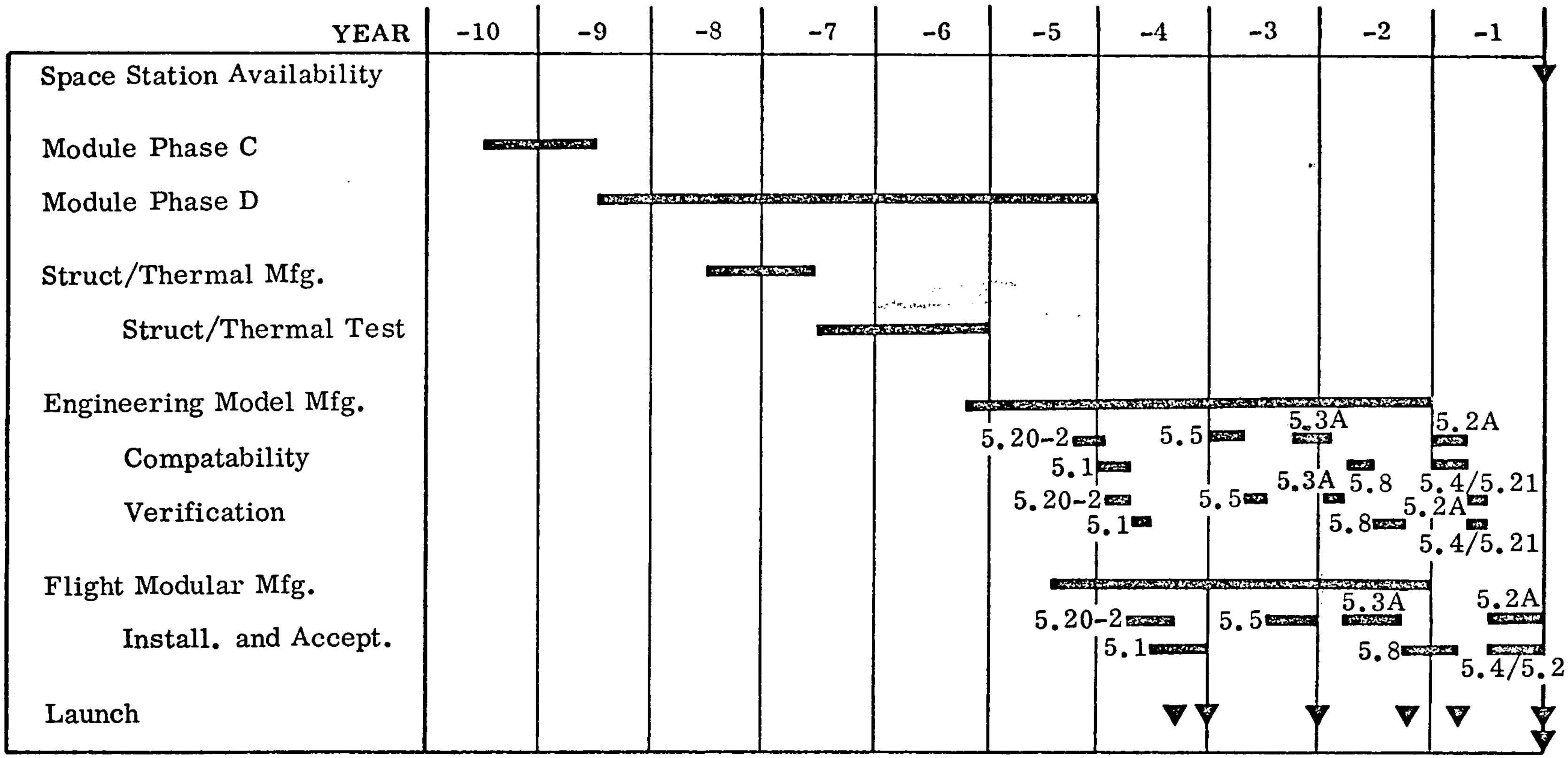


Figure 4-3. Preliminary CM-1 Summary Schedule

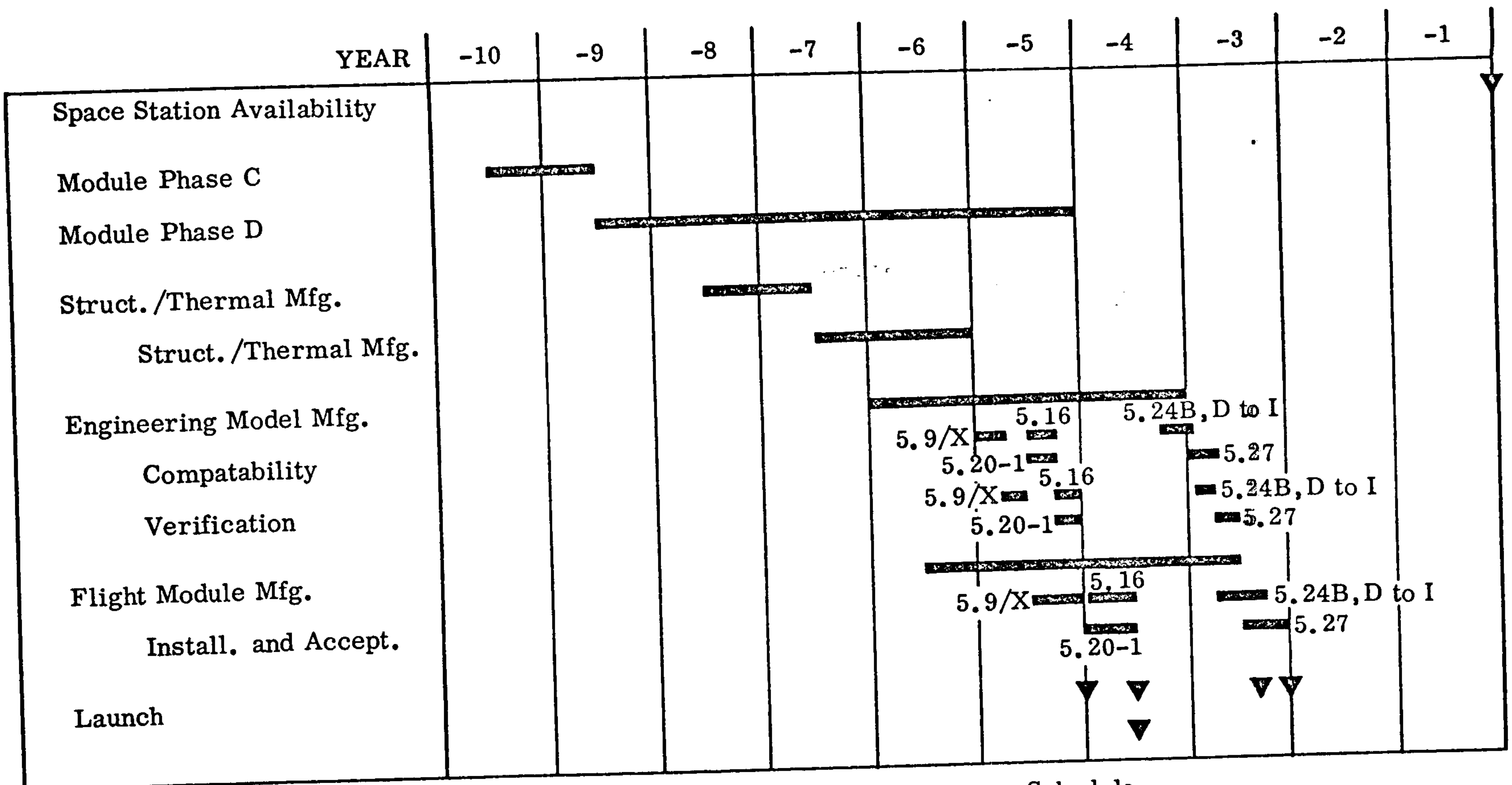


Figure 4-4. Preliminary CM-3 Summary Schedule

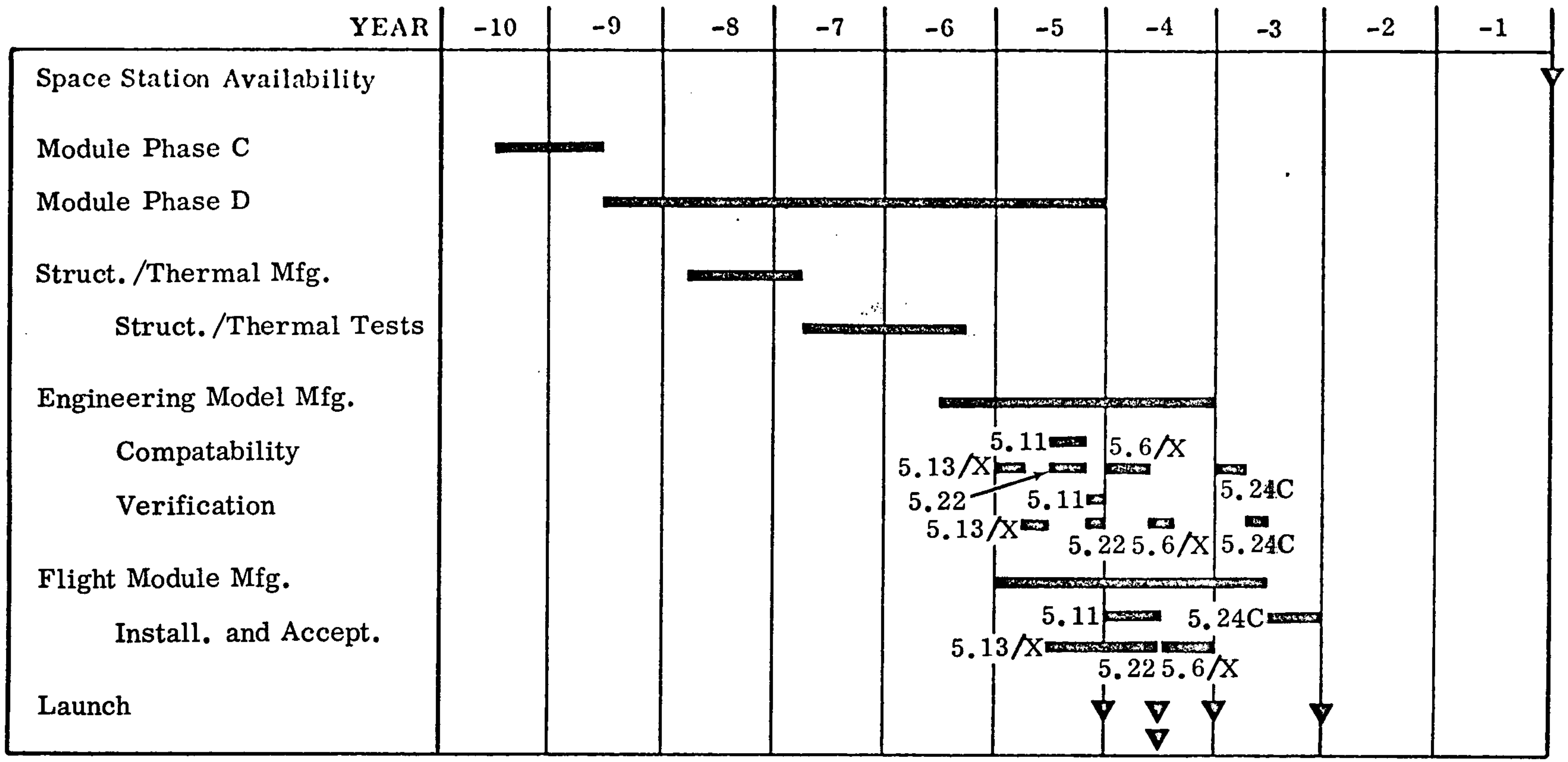


Figure 4-5. Preliminary CM-4 Summary Schedule

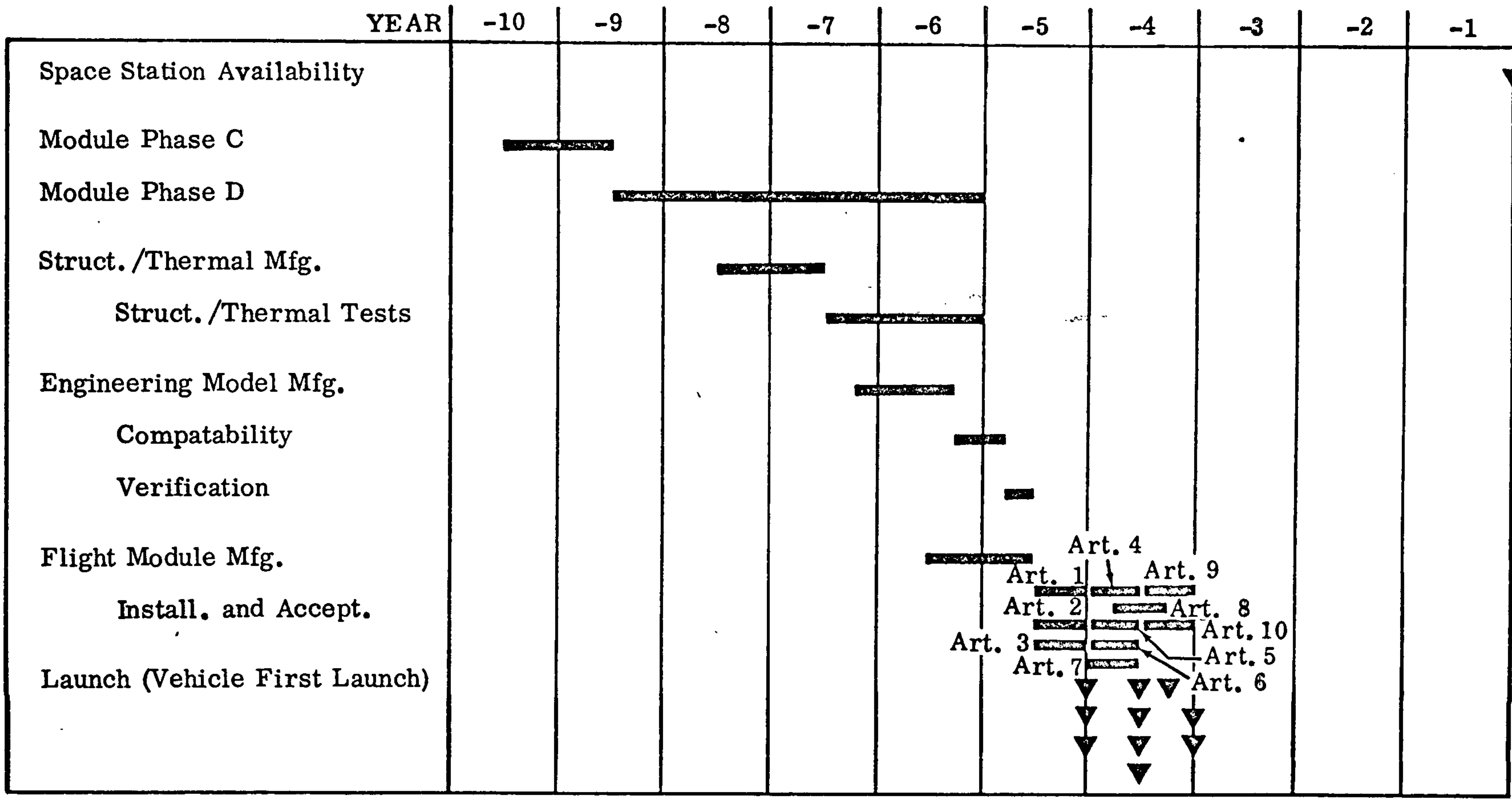


Figure 4-6. Preliminary Support Module Summary Schedule

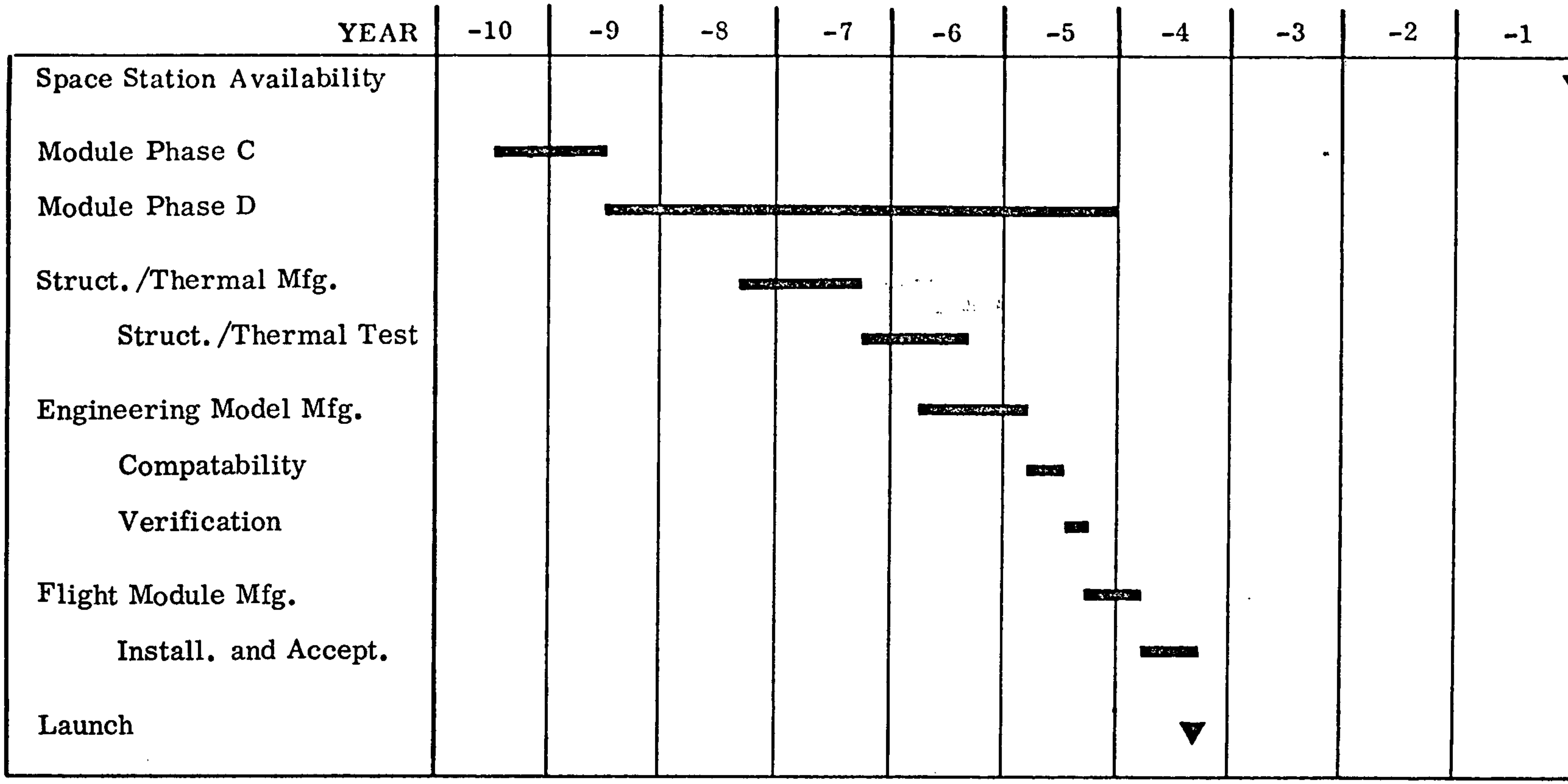


Figure 4-7. Preliminary Propulsion Slice Summary Schedule

SECTION 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The majority of the representative experiment program defined in the NASA Blue Book can be accommodated in the shuttle-only mode of experiment module operation. Such accommodation requires only kit additions to the baseline common module.

A five-day orbiter stay time will accommodate all experiments requiring free-flying operation. A 30-day stay time capability enables a comprehensive program of orbital research to be carried out in the attached mode utilizing a not unreasonable number of supporting shuttle flights. Necessary elements to the overall system are 7 free-flying experiment modules, one propulsion slice, and 10 attached modules, in conjunction with 10 support modules and 213 shuttle flights over a four-year period at a cost of $4.2B.

In the event that the space shuttle is to support an experiment module program, certain mission and design requirements should be considered in its development. These will include 30-day minimum on-orbit stay time, access requirements between shuttle crew compartment and experiment modules, and supplemental design of the reaction control subsystem to accommodate experiment pointing and stability requirements in a more efficient manner.

5.2 RECOMMENDATIONS

Items of major importance to be covered in any future studies of shuttle-only operations of experiment modules should include:

a. Consideration of the utility and effects of an ability to leave scientist-astronaut crews on orbit for specified periods of time without the shuttle in attendance — including crews larger than two men.

b. Study of the commonality effects of support module/experiment module interaction.

c. Special study of involved safety problems.

d. Attention to the reasonable design-driving requirements to be imposed on the shuttle orbiter to meet this operating mode.

e. Aspects of double-shuttle on-orbit operations, both for back-to-back experiment module manning and rescue/abort considerations.

INDEX OF FUNCTIONAL PROGRAM ELEMENTS

FPE NO.	TITLE	BASIC STUDY ASSIGNMENT
5.1	Grazing Incidence X-Ray Telescope	Module
5.2A	Stellar Astronomy Module	Module
5.3A	Solar Astronomy Module	Module
5.4	UV Stellar Survey	Space Station
5.5	High Energy Stellar Astronomy	Module
5.6	Space Physics Airlock Experiments	Space Station
5.7	Plasma Physics & Environmental Perturbations	Module
5.8	Cosmic Ray Physics Laboratory	Module
5.9	Small Vertebrates (Bio D)	Module
5.10	Plant Specimens (Bio E)	Module
5.11	Earth Surveys	Module
5.12	Remote Maneuvering Subsatellite	Module
5.13	Biomedical & Behavioral Research	Space Station
5.14	Man/System Integration	Space Station
5.15	Life Support & Protective Systems	Space Station
5.16	Materials Science & Processing	Module
5.17	Contamination Measurements	Module
5.18	Exposure Experiments	Module
5.19	Extended Space Structure Development	Space Station
5.20	Fluid Physics in Microgravity	Module
5.21	Infrared Stellar Survey	Space Station
5.22	Component Test & Sensor Calibration	Module
5.23	Primates (Bio A)	Module
5.24	MSF Engineering & Operations	Space Station
5.25	Microbiology (Bio C)	Space Station
5.26	Invertebrates (Bio F)	Space Station
5.27	Physics & Chemistry Laboratory	Module